# MONTHLY WEATHER REVIEW

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## OCTOBER 1954

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## MONTHLY WEATHER REVIEW

First published in 1872, the Monthly Weather Review serves as a medium of publication for technical contributions in the field of meteorology, principally in the branches of synoptic and applied meteorology. In addition each issue contains an article descriptive of the atmospheric circulation during the month over the Northern Hemisphere with particular reference to the effect on weather in the United States. A second article deals with some noteworthy feature of the month's weather. Illustrated. Annual subscription: Domestic, $3.00; Foreign, $4.00; 30¢ per copy. Subscription to the *Review* does not include the *Supplements* which have been issued irregularly and are for sale separately.

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(Continued on inside back cover)

The Weather Bureau desires that the *Monthly Weather Review* serve as a medium of publication for original contributions within its field, but the publication of a contribution is not to be construed as official approval of the views expressed.

The issue for each month is published as promptly as monthly data can be assembled for preparation of the review of the weather of the month. In order to maintain the schedule with the Public Printer, no proofs will be sent to authors outside of Washington, D. C.

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DEPARTMENT OF COMMERCE
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WEATHER BUREAU
F. W. REICHELDERFER, Chief

# MONTHLY WEATHER REVIEW

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## SYNOPTIC BACKGROUND FOR RECORD APRIL MINIMUM TEMPERATURE AT FIRST CONNECTICUT LAKE, N. H., APRIL 4–5, 1954

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[Manuscript received June 30, 1954; revised August 23, 1954]

### INTRODUCTION

At 0700 EST on the morning of April 5, 1954, Hollis H. Young, cooperative observer for the U. S. Weather Bureau at First Connecticut Lake, N. H., recorded a minimum temperature for the past 24 hours of −17° F. This extremely low value exceeded by 5° the previous April minimum of record for New England.

Because of the unusual nature of this temperature, an investigation was made into the attendant circumstances by the New England Climatological Section Center of the Weather Bureau. The First Connecticut Lake "Record of Climatological Observations" for April showed a maximum of +15° for the 24 hours ending at 0700 EST on the 5th and a temperature of +9° at the time of observation on the 5th. On the reasonable assumption that the +15° occurred during the late afternoon of the 4th, it seemed almost impossible for the temperature to drop by 32° and then rise by 26°, all within some 15 hours. Further investigation, however, revealed that the −17° was by no means as improbable as it first seemed. This paper presents the results of the investigation.

### LOCATION AND EXPOSURE

Mr. Young has served as cooperative observer for the Weather Bureau since October 1, 1919. He has therefore 35 years of experience, and his climatological reports over this long period have been considered outstanding in accuracy. Moreover, he verified by subsequent letter that the value of −17°, as entered on his monthly "Record of Climatological Observations," was correct. Hence there can be no doubt as to the genuineness of the reading.

The climatological station where this record was obtained is located in extreme northern New Hampshire, at a point 14.5 miles south of the tip of the State. Its coordinates are 45°06′ N. latitude, 71°17′ W. longitude; elevation of the instrument shelter is 1,660 ft. The northernmost portion of New Hampshire is shaped like a rough square, about 20 miles to each side. It is mountainous, well-watered, and forested country. The topography east of the Connecticut River to the Maine line is basically a confused set of small valleys running into the Connecticut Valley. This eastern part has the highest elevation of the region, with summits up to 3,600 ft. West of the river, there are two long and narrow valleys with three intervening ridges, all oriented northeast-southwest. Ridge elevations are generally in the 2,000 to 2,500-ft. range, valley bottoms 500 to 1,000 ft. lower, though the highest ridge point is over 3,100 ft.

The large-scale topographic features surrounding the First Connecticut Lake station have been outlined because the very low temperature under consideration suggests that cold-air drainage may have been an important contributory factor. With this possibility in mind, figure 1 has been reproduced to show the land surface details within a 3-mile radius of the station, and figure 2 gives a close-up of the terrain immediately surrounding it. The thermometer shelter is set on open, grassy, slightly sloping land, about 75 ft. away from the nearest building and 200 ft. away from the nearest line of trees.

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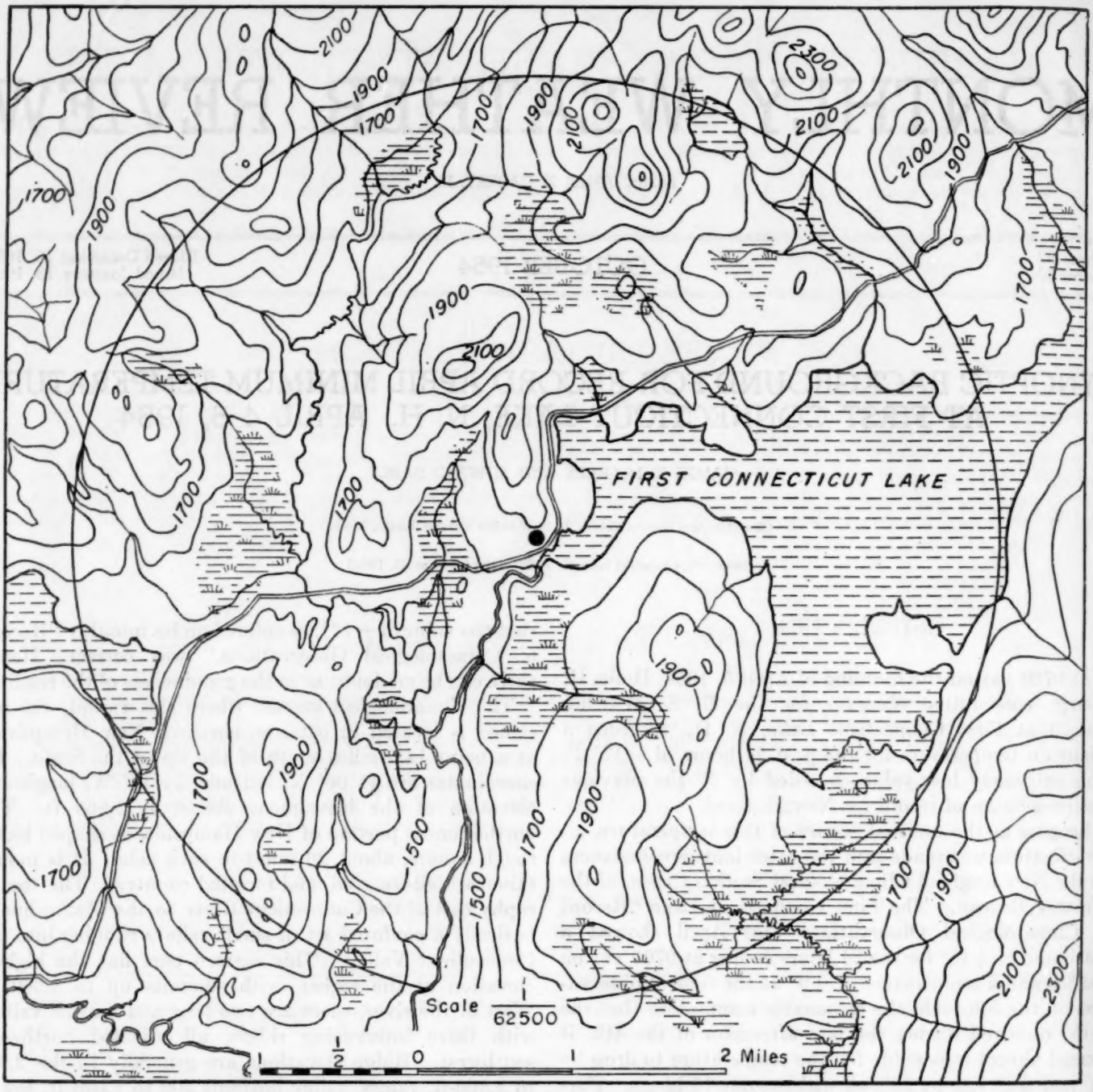


FIGURE 1.—Map showing topography within a 3-mile radius of cooperative observation station at First Connecticut Lake, N. H.

This is obviously an excellent exposure for a thermometer shelter, one which cannot be said to be influenced by any artificial heat- or cold-sources. Figures 1 and 2 indicate, however, that it is susceptible to cold-air drainage. The evidence of topography and exposure would seemingly demonstrate that the First Connecticut Lake station has an excellent location and is subject to local cold-air drainage under appropriate atmospheric conditions. Further, its elevation, latitude, and nearness (relative to most of New England) to the source region of Canadian air masses furnish additional support to the likelihood of its recording extremely low temperatures even in April. Finally, the fact that First Connecticut Lake has established several monthly minimum temperature records for New Hampshire shows that it is undeniably a "cold spot."

## SYNOPTIC SITUATION

Figures 3–8 present the series of 12-hourly surface weather maps and upper-air charts during the period from 0130 EST of April 4 to 1330 EST of April 5. Figure 3 shows that the northeastern United States was dominated on the night of April 3 and the morning of the 4th by an extensive anticyclone and an associated outpouring of

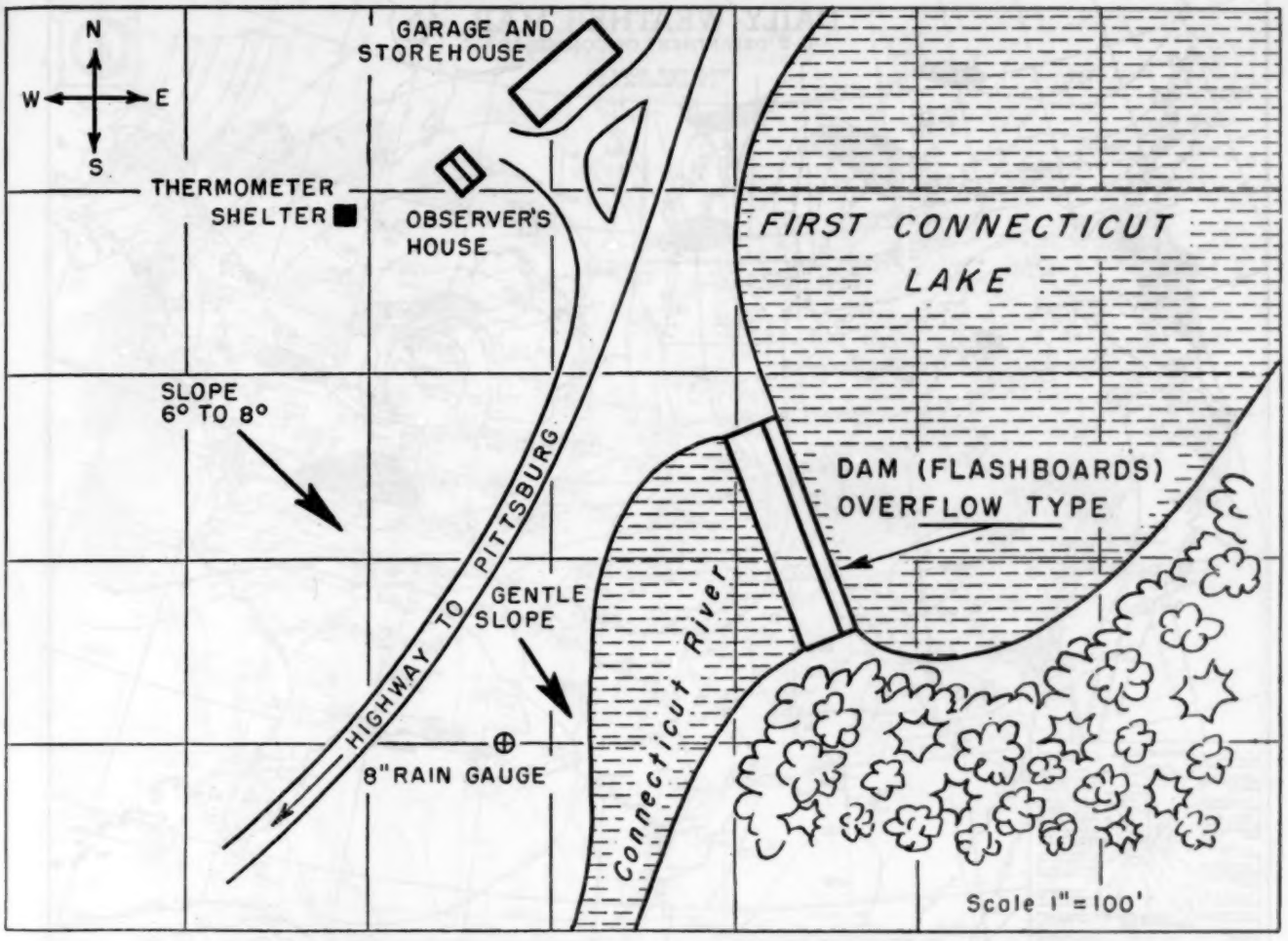


FIGURE 2.—Sketch map of details of immediate surroundings of station at First Connecticut Lake.

cP air from the Hudson Bay region of Canada. Winds were light to moderate and generally westerly over New England; skies were clear except in northern Vermont; temperatures were approximately 15°–20° below normal over the entire section. By 1330 EST of the 4th (fig. 4), the surface High had drifted eastward and the ridge-line, oriented in a northwest-southeast arc, extended across eastern New York State from the head of the St. Lawrence River to Long Island. New England continued to be on the cold side of the anticyclone, and afternoon readings on the 4th were decidedly subnormal. The 700-mb. constant-pressure chart for 1000 EST of the 4th (fig. 5) shows the strong upper-level northwest flow that was maintaining very low temperatures over New England.

Figure 6 represents the surface weather conditions at 0130 EST of the 5th. It is immediately apparent that the High, now centered off the Middle Atlantic Coast, has moved rapidly eastward during the previous 12 hours and that the ridge-line, though less distinct than on the earlier map, is probably located so that only Maine of the New England States still lies on the cold side. This latter point is significant, since it means that the minimum value of −17° read at First Connecticut Lake at 0700 EST of the 5th must have occurred close to 0130 EST of the same date.

Figure 6 assumes importance, then, in that it indicates the synoptic situation that existed within a few hours of the estimated time of occurrence of the record minimum. The map shows either calm conditions or light to gentle variable winds over New England, clear skies except for Connecticut and (probably) the western Massachusetts-southern Vermont region, and continued subnormal temperatures. A glance at the map with a view toward explaining the −17° at First Connecticut Lake reveals that the surface weather situation favored strong nocturnal radiation. Moreover, it favored local cold-air drainage, a possible contributory factor considered in the previous section of this paper.

Figures 7 and 8 are the surface map and 700-mb. chart for 1330 EST and 1000 EST, respectively, of the 5th. A comparison of these with figures 4-6 reveals a striking change in the circulation pattern over New England. At the surface, the incipient southwesterly flow and consequent warming trend suggested by figure 6 are realized in figure 7. Aloft, the cold northwesterlies that dominated the region have been replaced by vigorous westerlies and

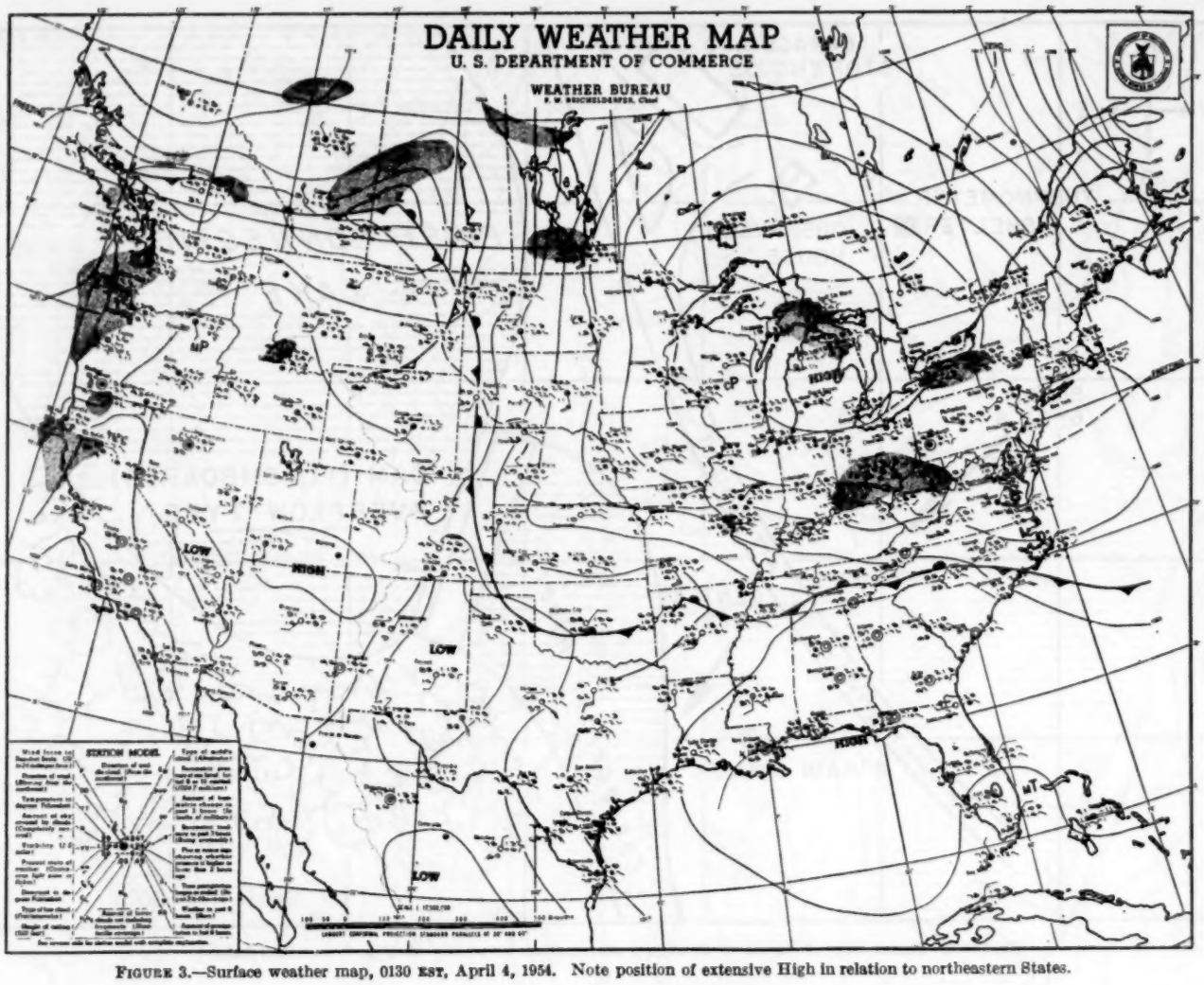


FIGURE 3.—Surface weather map, 0130 EST, April 4, 1954. Note position of extensive High in relation to northeastern States.

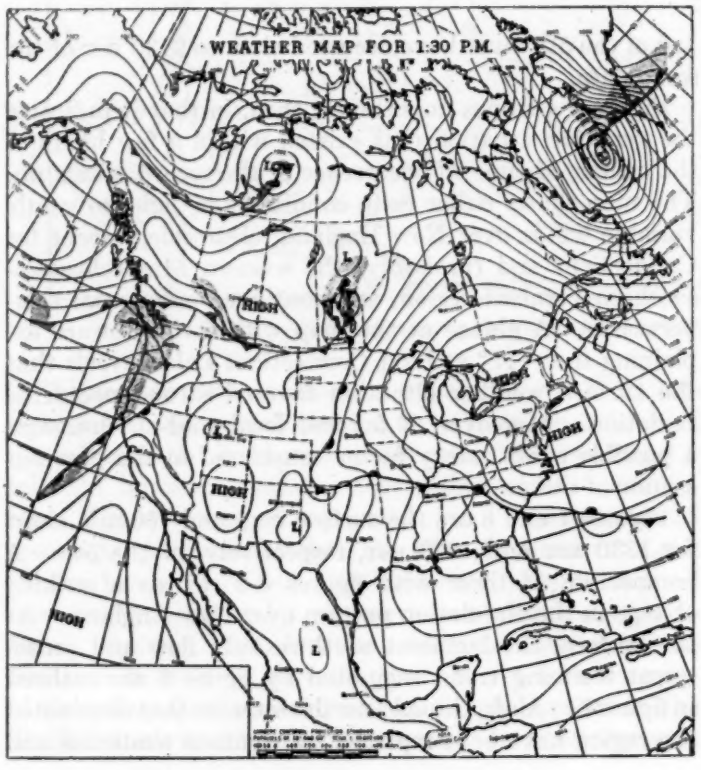


FIGURE 4.—Surface weather map, 1330 EST, April 4, 1954.

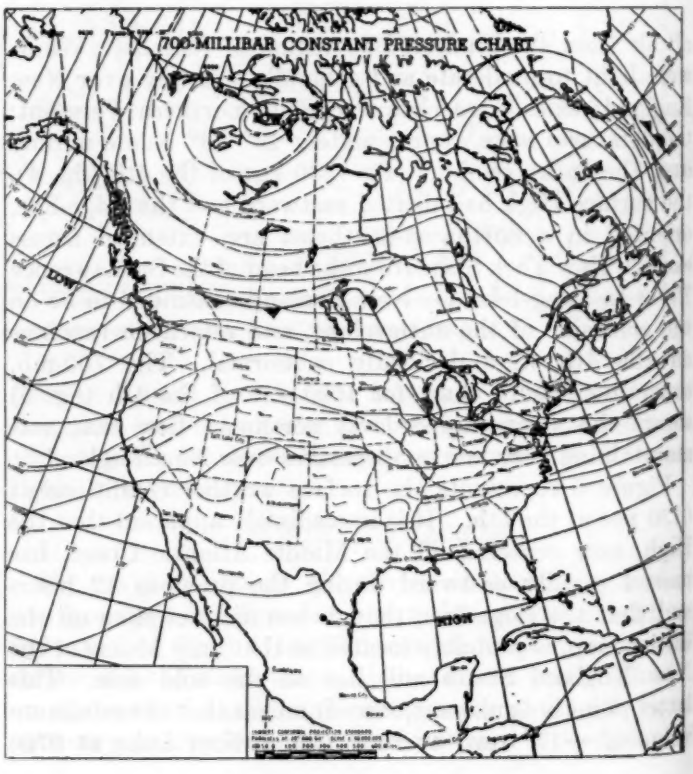


FIGURE 5.—700-mb. chart, 1000 EST, April 4, 1954.

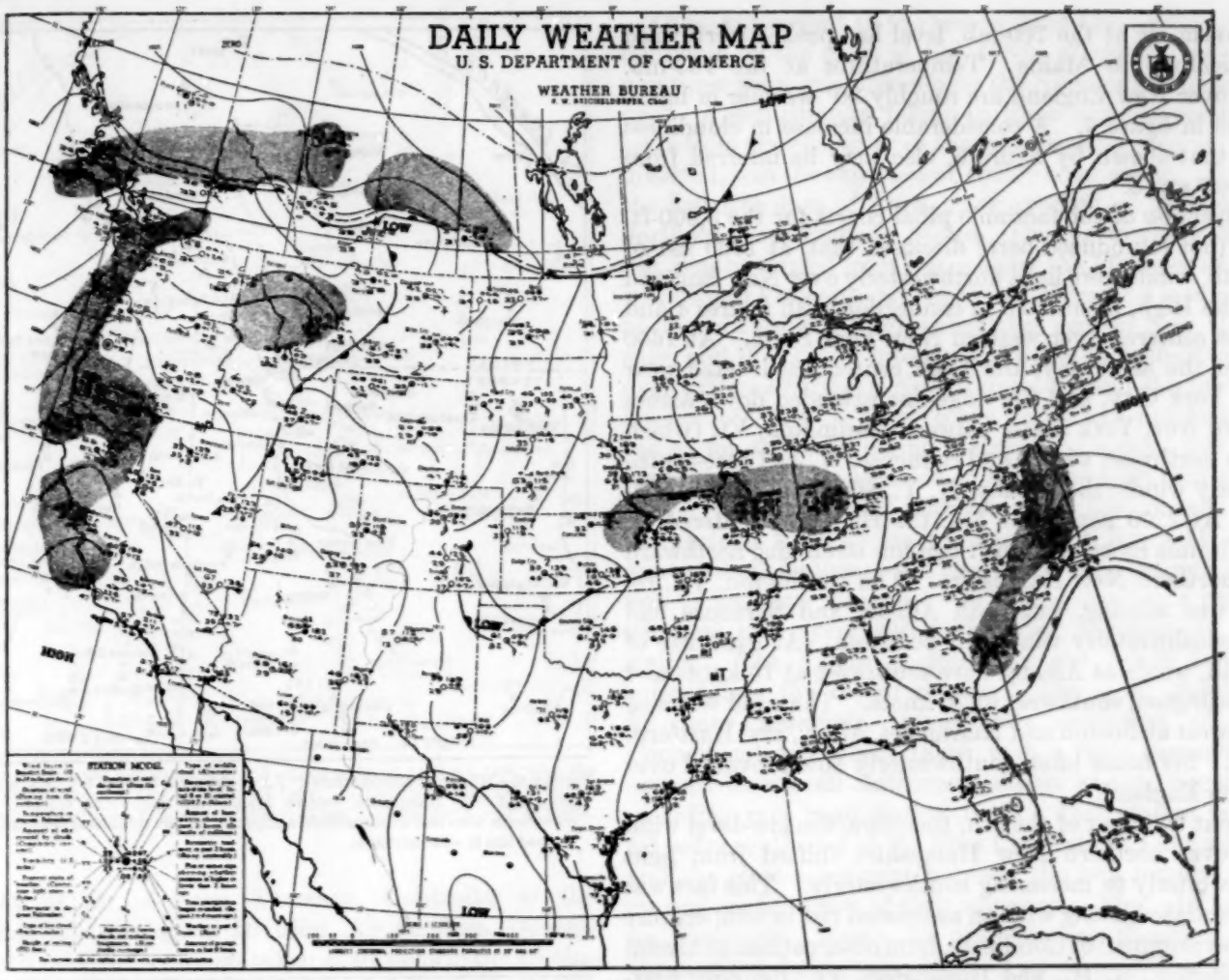


FIGURE 6.—Surface weather map, 0130 EST, April 5, 1954, near the time of occurrence of the record minimum at First Connecticut Lake station.

FIGURE 7.—Surface weather map, 1330 EST, April 5, 1954. Note the change in position of High from figure 3 and consequent change in wind direction and temperatures over northeastern States.

FIGURE 8.—700-mb. chart, 1000 EST, April 5, 1954. Compare with figure 5.

the warm air at the 700-mb. level has pushed northward practically into Maine. Temperatures at the 700-mb. level over New England are roughly 20° warmer in figure 8 than in figure 5. A considerable increase in cloudiness over that shown by figure 6, also may be inferred from figures 7 and 8.

Inspection of the facsimile pibal charts for the 3,000-ft. level (not reproduced here) disclosed that, at 1000 EST of the 4th, winds were light northwesterly over New England and the High, mentioned in connection with figures 4 and 6, was centered over western New York State. At 1600 EST of the same day, the High center was located near New York City, and the ridge-line extended down across eastern New York State, between Burlington, Vt. (which had a northwest wind), and Syracuse, N. Y. (west-southwesterly wind); the Albany, N. Y., wind report was missing. At 2200 EST of the 5th, the High was centered off the Virginia coast, with the ridge-line stretching northward into northern New Hampshire. The Burlington, Vt., report was missing, but both Albany and Syracuse had west-southwesterly winds, 15–20 knots. At 0400 EST of the 5th, winds at Albany were southwest at 10 knots and at Burlington, southwest at 20 knots. The wind was also southwest at Boston and Nantucket, Mass., and Hartford, Conn. Six hours later, southwesterly flow prevailed over all New England.

About 0400 EST of the 5th, therefore, the low-level wind field over northern New Hampshire shifted from light northwesterly to increasing southwesterly. This fact was substantiated, along with an associated rise in temperature and development of cloudiness, from observations at Mount Washington, N. H., and Burlington, Vt., the only first-order stations within 100 miles of First Connecticut Lake.

From this analysis of the pertinent synoptic features between the morning of April 4 and the afternoon of April 5, a working hypothesis may be developed to account for the First Connecticut Lake minimum: (1) The −17° occurred between 0130 EST and 0400 EST of the 5th. (2) It was produced by the presence of unseasonably cold Canadian air under circumstances which favored a rapid temperature drop, of the order of 30° between sunset of the 4th and (approximately) midnight. (3) These circumstances were, primarily, clear skies and calm or very light general winds, and secondarily, local cold-air drainage. (4) By about 0400 EST of the 5th, these conditions were abruptly reversed. Warmer air and cloudiness moved in swiftly from the southwest, causing a temperature rise of the order of 25°, between midnight and 0700 EST of the 5th.

## REGIONAL WEATHER

It has been shown (see figs. 3–5) that northern New England was engulfed on April 4–5 by an extremely cold continental polar air mass. In figures 9–11 are plotted the temperatures that occurred on these dates at a number of stations in the northern two-thirds of Vermont and New Hampshire and the western half of Maine. Through the

FIGURE 9.—Minimum temperatures (° F.) on the night of April 3–4, 1954, in upper Vermont and New Hampshire, western Maine, and neighboring Quebec. Values in parentheses were read from unofficial equipment but are considered reasonably reliable. Dashed line is −10° isotherm.

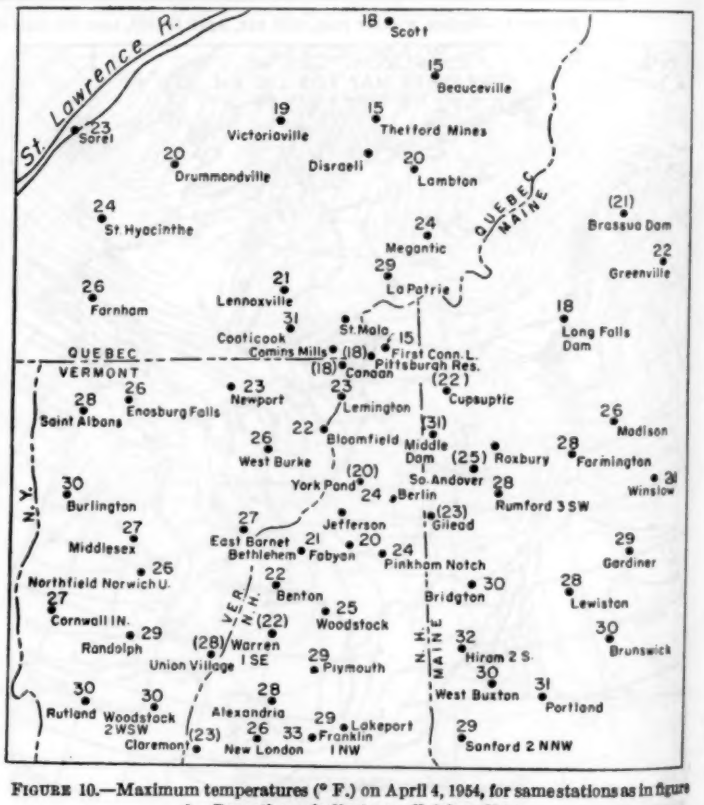


FIGURE 10.—Maximum temperatures (° F.) on April 4, 1954, for same stations as in figure 9. Parentheses indicate unofficial readings.

FIGURE 11.—Minimum temperatures (° F.) on the night of April 4–5, 1954, when the record −17° occurred at First Connecticut Lake. Stations are those used in figures 9 and 10 and parentheses indicate unofficial readings. Dashed line is −10° isotherm.

courtesy of Dr. Andrew Thomson, Controller of the Canadian Meteorological Division, Air Services, Department of Transport, readings taken at stations in the adjoining portion of the Province of Quebec are also included. Values enclosed in parentheses are from unofficial thermometric equipment. The equipment is standard in most cases, however, and the values are considered sufficiently reliable for use in this analysis.

Figure 9 gives the minimum readings on the night of April 3–4, when the outpouring of cold Canadian air, shown in figure 3, was the dominant regional weather control. Subzero temperatures covered a wide area in the upper Connecticut Valley, along the northern Maine boundary, and the bordering region of Quebec. The rest of the area in figure 9 had temperatures generally in the 0° to +10° range. The normal minimum values for this time of year range from approximately 30° in the south to 15° in the north, so that the temperatures shown in figure 9 average some 15°–20° below normal.

In figure 10 are shown the maximum temperatures for April 4. They range from the low 30's in the southern portions of Vermont, New Hampshire, and Maine, to the high and middle teens in the mountains of northern New Hampshire, in northern Maine, and the adjacent part of Canada. Temperatures in the 20's predominate over most of the area shown in figure 10. These readings are generally 20°–25° below normal.

Thus, antecedent to the record First Connecticut Lake minimum on the night of the 4–5th, extremely low temperatures were established over the region under examination. A contributing factor to these low temperatures, aside from the character of the unseasonably cold air mass involved, was the existence of a deep snow cover. During the first five days of April, snow overlaid all three of the northern New England States. On the morning of the 5th, depths ranged from traces along the Maine coast, and in southern Vermont and New Hampshire, to 6 inches over northern Vermont, 6–20 inches over central New Hampshire and the central interior of Maine, and 20–30 inches over extreme northern New Hampshire and the northern interior of Maine. Snow cover data have not been obtained for the neighboring district of Canada, but they may reasonably be assumed to be in the 6–20 inch range.

The stage was set, therefore, for the record First Connecticut Lake minimum as shown in figure 11. The most striking feature of this chart is perhaps the concentration of very low minima (−10° and below) in a roughly elliptical area lying about the First Connecticut Lake station. The values enclosed by the −10° isotherm substantiate the record reading. The −16° shown for Pittsburg Reservoir, immediately southwest of First Connecticut Lake, was taken with a Six's thermometer exposed in a small instrument shelter at the cooperative recording rain gage station there. This station is only 5.5 miles southwest of the First Connecticut Lake station, and the close agreement between the two minima offers mutual confirmation of their accuracy. The −16° shown for Cupsuptic, Maine, 25 miles east-southeast of First Connecticut Lake, was observed at an unofficial station using standard thermometers and Weather Bureau-type shelter. Exposure of instruments and quality of temperature readings there are good. The −13° at the Canaan, Vt., cooperative (precipitation only) station, was measured with a reliable U-tube thermometer installed in a well-exposed but small shelter. No information is available on the Canadian station at Comius Mills, where −13° also occurred on the night of the 4–5th. The −12° at the Lemington, Vt., full climatological station, taken with official equipment, equalled the previous April low reading for New England and constituted a new monthly minimum record for Vermont.

## CONCLUSION

It would seem well established, therefore, that a very cold core of air was settled on the night of April 4–5, 1954, over an area roughly 35 miles in diameter and centered on First Connecticut Lake. This air mass was unseasonably chilly to begin with, and extreme minimum temperatures were favored by the presence of a deep snow cover and ideal nocturnal radiation conditions until approximately 0400 EST of the 5th. As previously suggested, local air drainage may also have contributed to the −17° reading.

After 0400 EST the regional atmospheric circulation changed suddenly and radically, to advect milder air with increased sky cover, but not before a new April minimum temperature record for New England had been established. It may be of interest to note that, except for a reading of −24° at North Lake, N. Y., on April 1, 1953, no temperature lower than the First Connecticut Lake value has ever been recorded during April in the entire northeastern United States.

## ACKNOWLEDGMENTS

The authors wish to thank those whose information and advice aided materially in the preparation of this paper. These include: Dr. Andrew Thomson, Controller, Meteorological Division of the Canadian Department of Transport; Weather Bureau officers at Caribou and Portland, Maine, Concord, N. H., Burlington, Vt., and Albany, N. Y.; Cooperative Observers in northern New England, especially Mr. H. H. Young at First Connecticut Lake, N. H., Mr. C. L. Covill, Engineer at Murphy Dam, Pittsburg, N. H., and Mr. E. F. Fenn of the Brown Co. at Berlin, N. H.; and Mr. Morton J. Rubin of the Southern Hemisphere Unit of the U. S. Weather Bureau at Boston, Mass.

## CORRECTION

Monthly Weather Review, Chart VIII: Correct coordinates for the solar radiation equipment at Oak Ridge, Tenn., are 35°55′ N., 84°19′ W. Data for Oak Ridge have been plotted about 140 miles too far northeast in previous issues.

# A SURFACE STUDY OF A DEPRESSION-TYPE PRESSURE WAVE

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[Manuscript received August 13, 1953; revision received November 18, 1954]

## ABSTRACT

A study is made of the surface micro-features of a depression-type pressure wave that passed across the Cloud Physics network in southwestern Ohio, April 7, 1948. Pressure change, wind, rain, temperature, and humidity observations in the network are described with the aid of isochrone charts and micro-synoptic charts at 5-minute intervals. Comparison of the micro-charts with a section of the conventional surface weather map suggests a possible linkage between the depression-type wave and a squall line or pressure jump line.

## INTRODUCTION

During the past several years considerable interest has been shown in atmospheric pressure waves, especially those in which an abrupt rise in pressure occurs. Tepper's pressure jump theory [1, 2] is an outstanding example. Many investigators have also noted an opposite type wave in which there is an abrupt fall in pressure. Brunk [3, 4] calls it a "pressure pulsation," and suggests that in extreme cases it may develop into a tornado. Tepper [2, 5] calls it a "depression-type wave" that is propagated along an inversion surface, and has reported a case in which a cloud bank was desiccated upon passage of the wave. Williams [6] has observed that depression-type waves frequently follow the passage of elevation-type waves or pressure jumps.

Depression-type waves are a meteorological oddity In spite of the intense pressure falls associated with them' they do not generally coincide with severe weather or even "bad" weather. For this reason there appears to be little justification for even noticing them. On the other hand, it is interesting to note just what weather conditions may occur with an intense depression-type wave. This paper is a descriptive presentation of the surface micro-features of one such wave.

The case of April 7, 1948, is presented, using data from the 1948 Cloud Physics Project, Wilmington, Ohio. The Project network, which has been described elsewhere [7], provided graphic records of pressure, temperature, relative humidity, rainfall, wind direction, and wind speed at 55 surface stations distributed over a small area (8 miles by 20 miles).

## MICRO-SYNOPTIC FEATURES

### PRESSURE

The changes in pressure were striking. The reproduction of 12-hour barograms in figure 1 shows the pattern of pressure change at each station. Even over this small area there was considerable variation in the pressure change pattern.

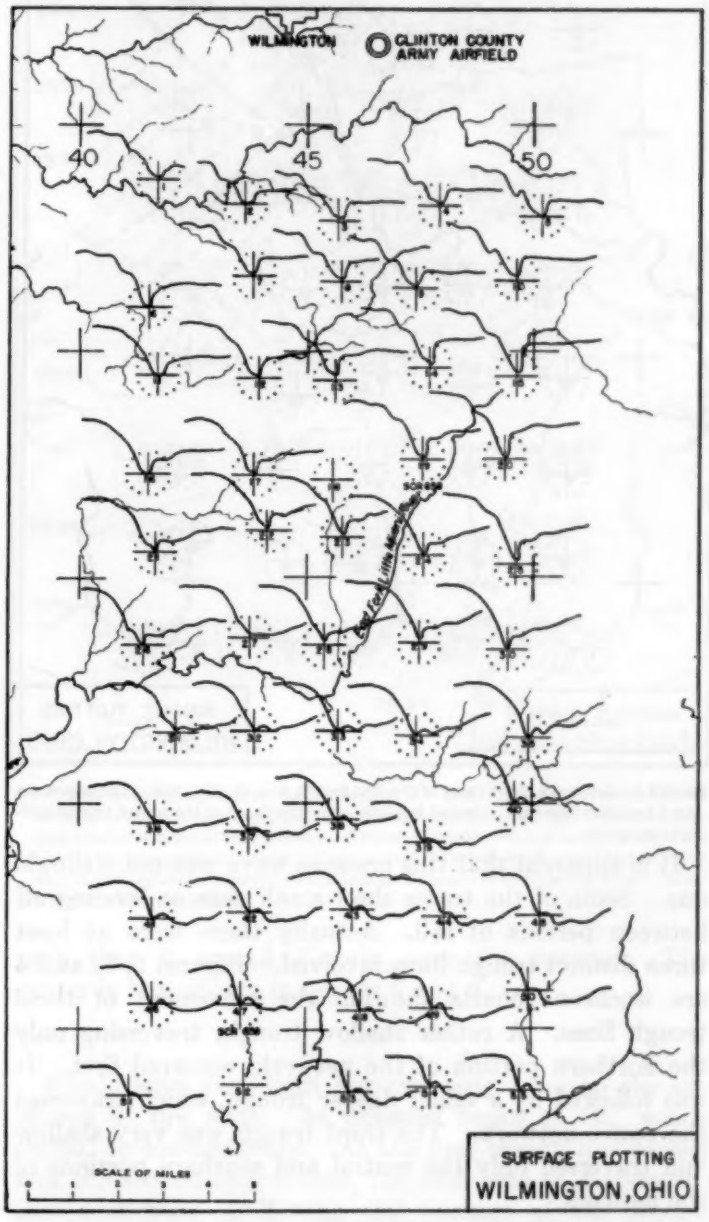


FIGURE 1.—Reproduction of 12-hour barograms, showing the pattern of the depression wave at each station in the Cloud Physics network, April 7, 1948.

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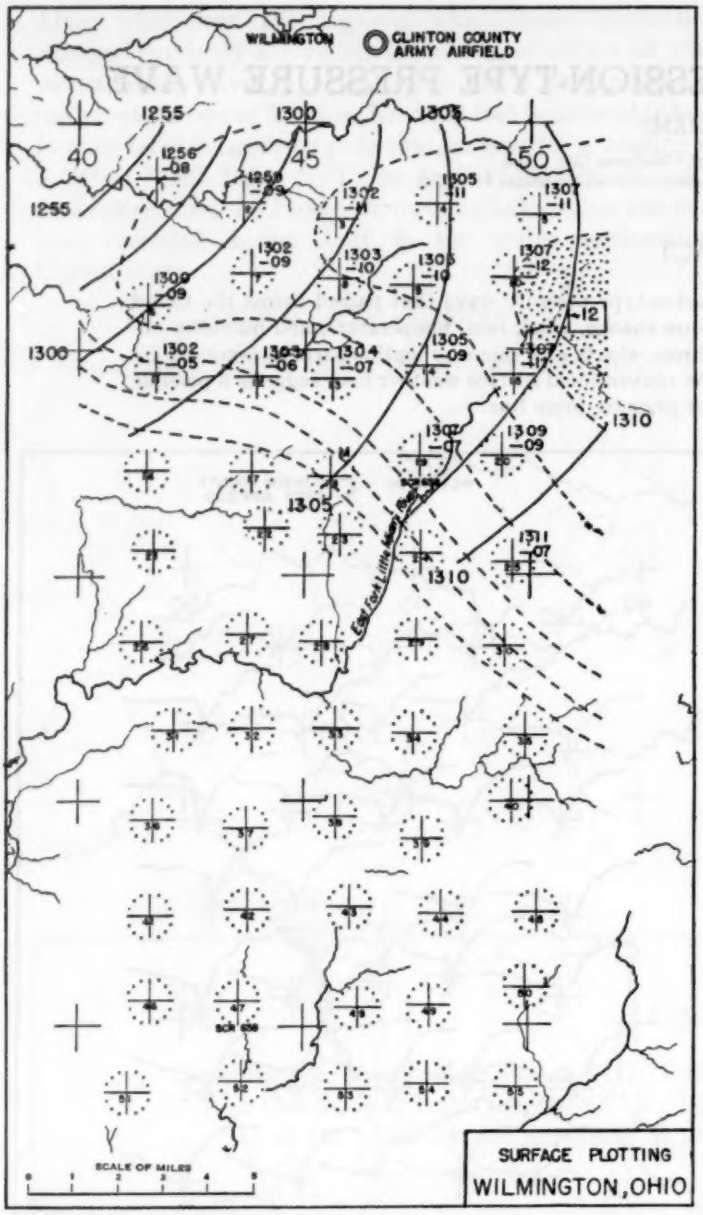


FIGURE 2.—Isochrone chart (EST) of the first trough line, April 7, 1948. Isochrones are for 2.5-minute intervals. Dashed isopleths show the depth of the trough line for 0.02-inch intervals.

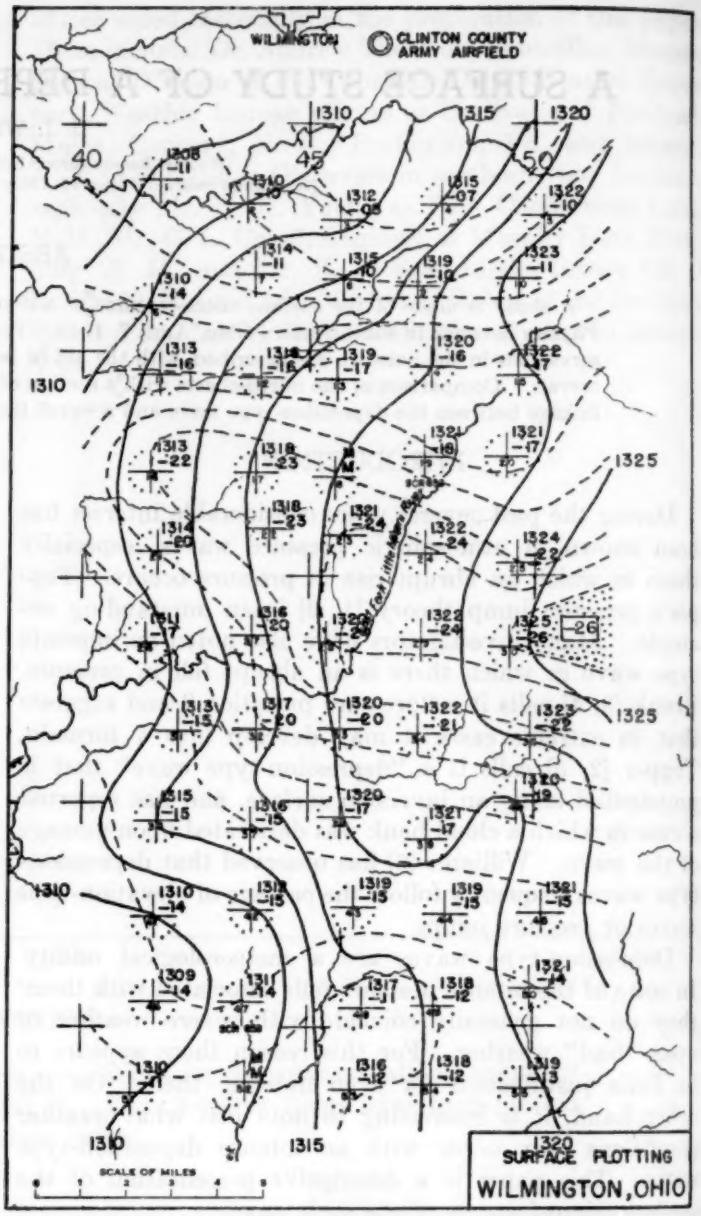


FIGURE 3.—Isochrone chart (EST) of the second trough line, April 7, 1948.

It is apparent that this pressure wave was not a simple one. Some of the traces show small rises or leveling off between periods of fall. Actually there were at least three distinct trough lines involved. Figures 2, 3, and 4 are isochrone charts showing the movement of these trough lines. A rather shallow trough, traversing only the northern portion of the network, occurred first. It was followed by a much deeper trough, which traversed the entire network. The third trough was very shallow and traversed only the central and southern portions of the network.

Depths of the first and second troughs increased as they moved eastward. Depth of the first was 0.12 inch by the time it passed off the network at Station 10. Depth of the second was 0.26 inch when it passed off the network at Station 30. The third trough had a maximum depth of 0.06 inch along the southern tier of stations. It is possible that greater depths may have been attained beyond the network.

The first trough line was fairly uniform in curvature. The second and third were very irregular. In fact, the curvature of the second was so irregular in the vicinity of Stations 36–45 that its continuity is in doubt. There may have been two trough lines, not quite joined together, in this vicinity.

Average movement of trough lines was from west to east, and speeds along paths of maximum depth averaged from 46 to 48 mph. There was considerable variation from average values; e. g., the speed of the second trough apparently reached 90 m. p. h. for a 2.5-minute period in the vicinities of Stations 18, 19, and 20.

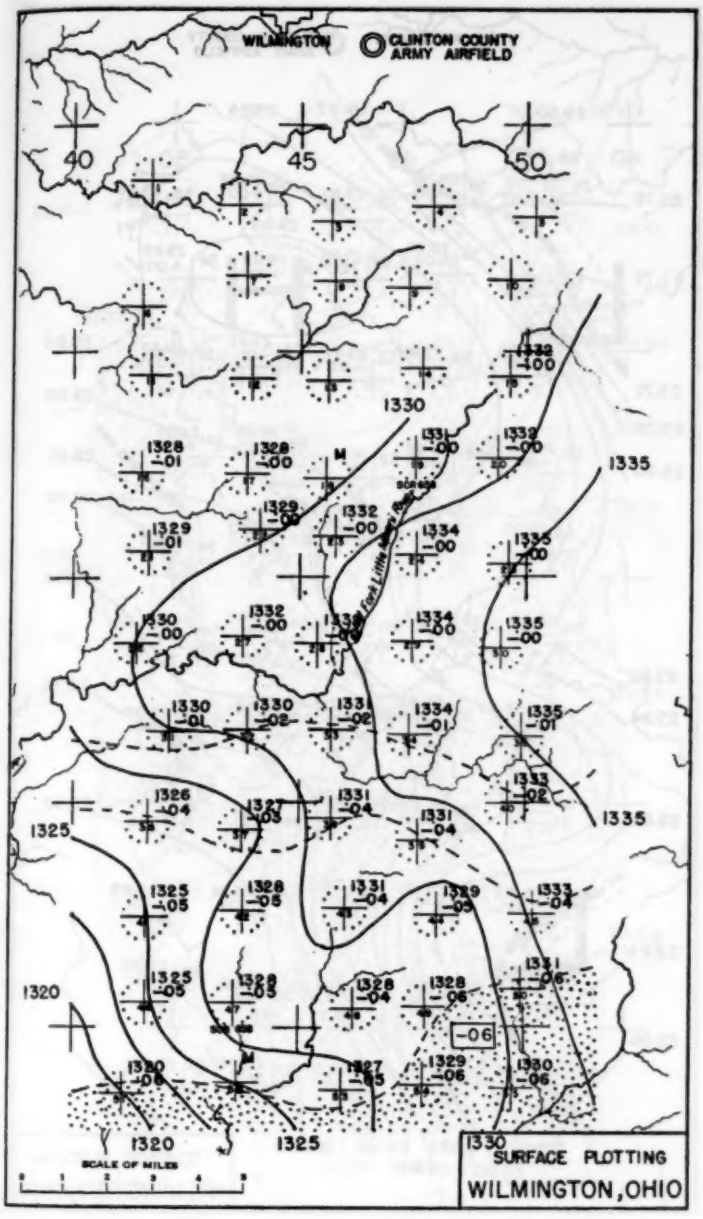


FIGURE 4.—Isochrone chart (EST) of the third trough line, April 7, 1948.

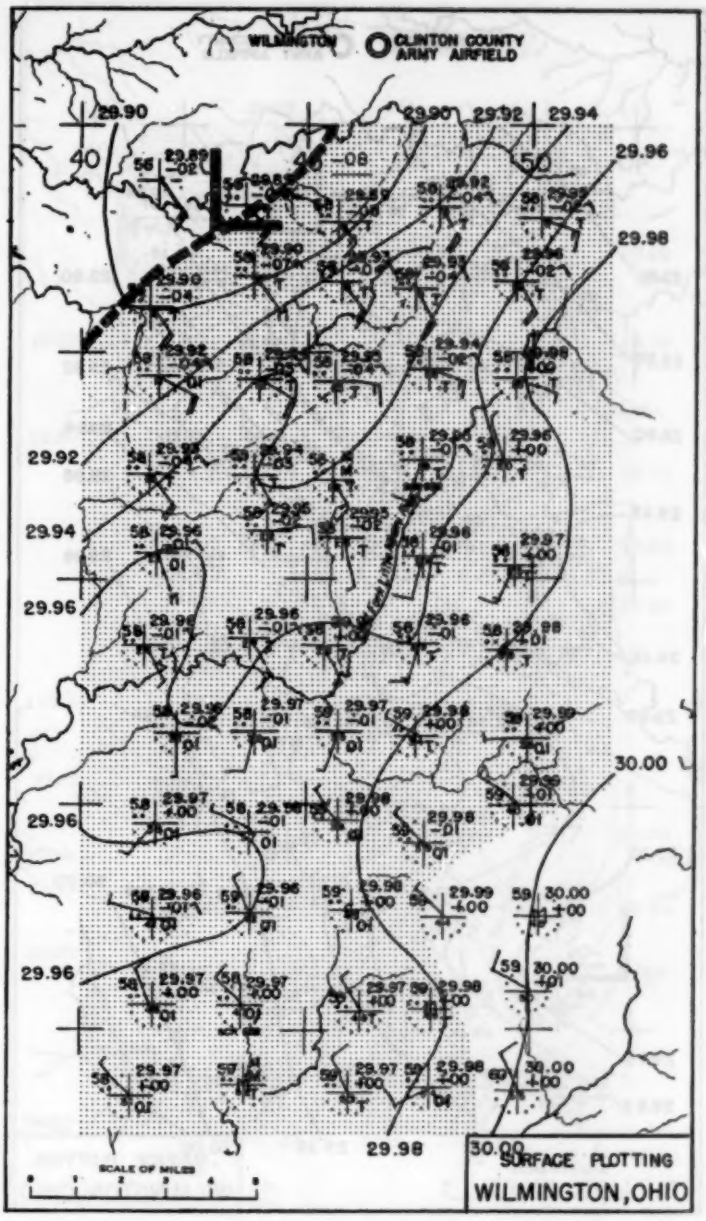


FIGURE 5.—Micro-synoptic chart for 1300 EST, April 7, 1948. Data are plotted as follows: Sea level pressure in inches of Hg; pressure tendency in hundreths of inches per 5 minutes; rainfall in hundreths of inches per 5 minutes; temperature, present weather, and wind in the conventional manner. Chart is analyzed as follows: Trough line as a heavy dashed line; isobars for each 0.02 inch; isallobars for each 0.04 inch per 5 minutes. Areas of precipitation are stippled.

Pressure changes are most graphically shown in the 5-minute micro-synoptic charts in figures 5–11. Rates of fall as great as 0.13 inch per 5 minutes (Station 20, fig. 9) occurred, and gradients as great as 0.08 inch per mile (vicinity of Station 11, fig 7.) occurred. These values are comparable to those observed in squall lines investigated from similar data [7] and are 50 to 100 times greater than normally observed in intense macro-systems.

Stations in the northern portion of the network showed abrupt pressure rises following the passage of the second trough line. Except for the abrupt falls preceding them, these rises resembled pressure jumps. However, they were lacking in other features, such as gusty, shifting winds, thunderstorms, and temperature breaks that often accompany pressure jumps.

A closed low center on the wave was fortunately located such that it passed directly over the network. The center is best shown in figures 8 and 9.

## WIND

Winds were very light northwesterly prior to the approach of the wave. As pressure began to fall, winds shifted to southeasterly. As the first trough line passed and the second approached, the shift was to east-southeast and east. Following the passage of the second trough line winds did not shift again until pressure began to rise; then there were weak shifts to northeast and north. The passage of the third trough line did not appreciably alter the direction of the winds in the southern

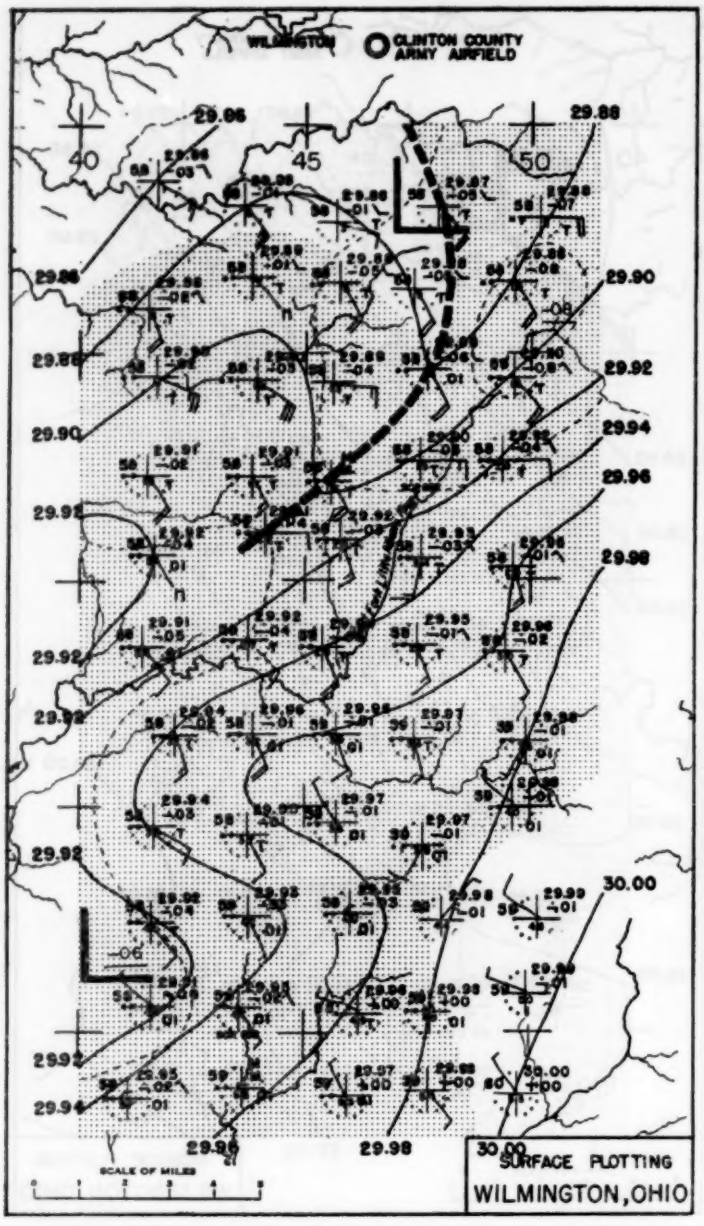


FIGURE 6.—Micro-synoptic chart for 1305 EST, April 7, 1948. The first trough line has moved to the north central portion of the network.

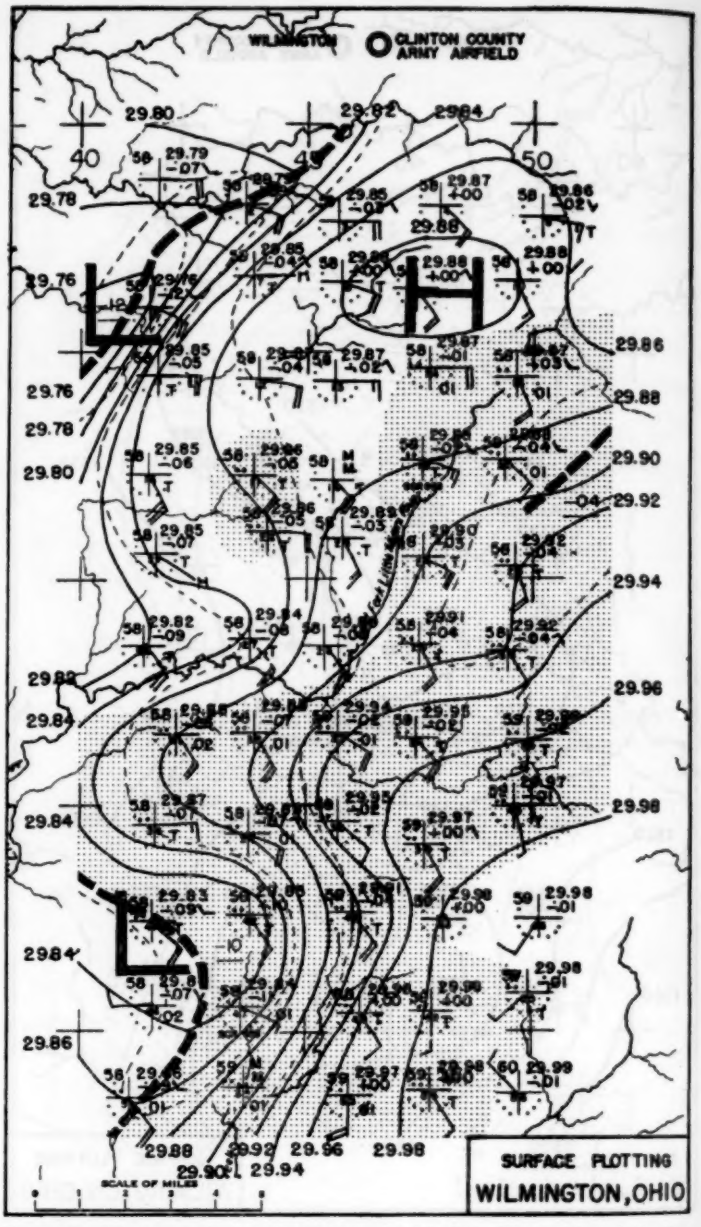


FIGURE 7.—Micro-synoptic chart for 1310 EST, April 7, 1948. The first trough line has passed off the network and the second trough line is entering the network at the northwest and southwest.

portion of the network; they remained generally from the southeast.

Wind speed prior to the approach of the wave was very light—less than 5 m. p. h. As pressure began to fall, wind speed increased. Maximum speeds from 21 to 38 m. p. h. were reached 5 to 10 minutes later. In some instances speeds remained high for several minutes; in others speeds diminished steadily following the maximum. Double maxima were recorded at some stations because of the approach of two separate trough lines. In general, speeds increased as trough lines approached and decreased after their passage. Speeds were generally greatest in areas of maximum pressure gradient, but destructive speeds were never attained. Wind speeds in excess of 30 m. p. h. were attained at 13 stations. The maximum speed of 38 m. p. h. was recorded at Station 24.

Winds did not conform to the pressure fields in the manner of macro-systems. They tended to blow at right angles to the isobars toward lower pressure, perhaps in response to isallobaric gradients. As the pressure troughs moved, there was an appreciable lag in the shifting of the winds to their pre-trough directions.

Although winds increased as pressure gradients increased, the speeds of 21 to 38 m. p. h. were exceedingly small in relation to the gradients. A regression of wind speed on depth of the trough yielded an average speed of 1.32 m. p. h. for each 0.01 inch depth with a range from 1.10 to 1.76 m. p. h. Brunk [3] has made a similar regression for another case. His results give the wind speed in miles per hour equal to one-half the numerical value of the total pressure fall expressed in tenths of millibars. This formula applied to the April 7, 1948,

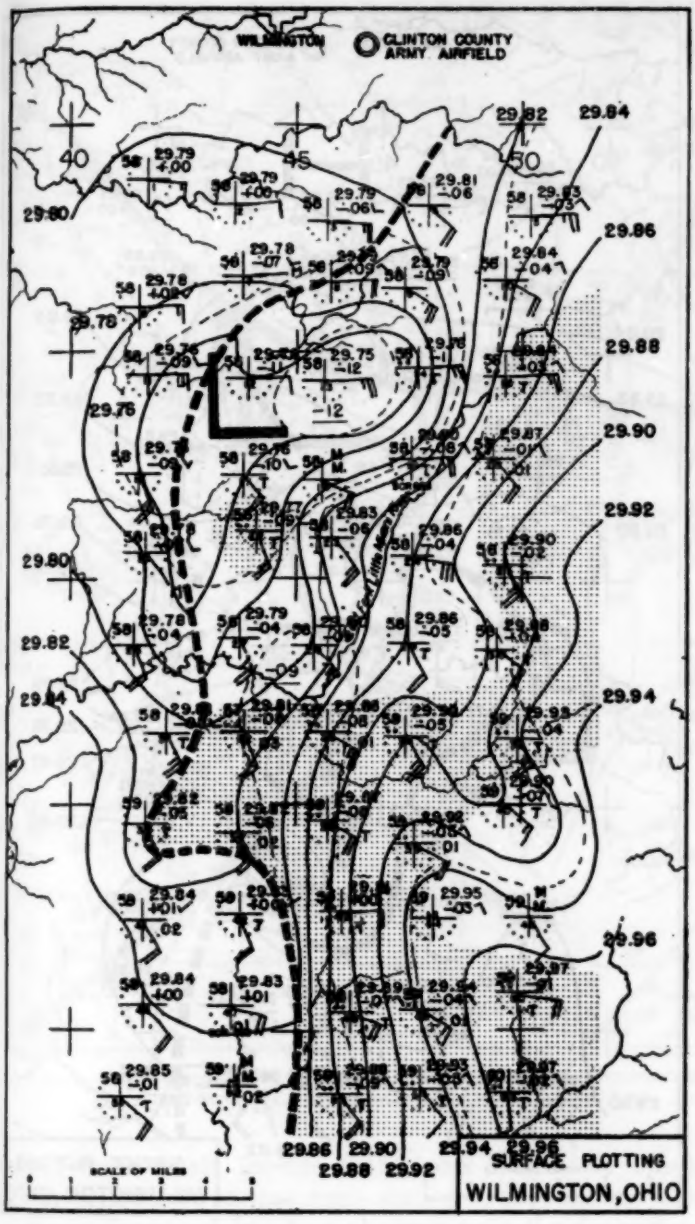


FIGURE 8.—Micro-synoptic chart for 1315 EST, April 7, 1948. The second trough line is now over the network.

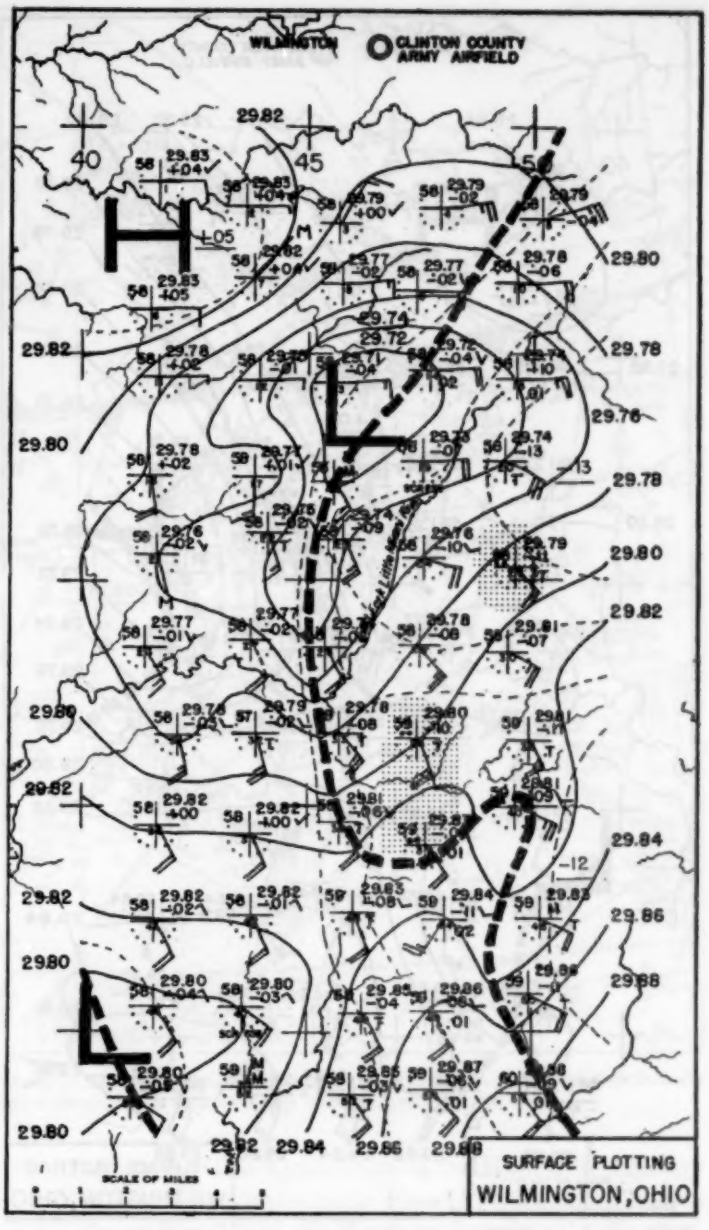


FIGURE 9.—Micro-synoptic chart for 1320 EST, April 7, 1948. The second trough line has moved eastward, while the third trough line is just entering the network at the southwest. A micro-High is beginning to build at the northwest.

case gives an average wind speed of 1.70 m. p. h. for each 0.01 inch depth of the trough. The value is a little high and suggests that perhaps an empirical formula should include the rate of pressure fall, as well as the amount of fall.

### RAINFALL

Rain fell over virtually all of the network prior to the passage of the wave and had begun 1 to 2 hours prior to its approach. It may be inferred from the sectional synoptic chart, figure 12, that this rain was due to thunderstorm activity. The amount of rainfall was light; the greatest amount measured at any one station was 0.09 inch. Most significant is the fact that rain ceased as the depression wave passed. Rain ceased in the northern tier of stations upon passage of the first trough line, and had diminished over the northern third of the network before passage of the second trough line. Rain in the remaining areas ceased upon passage of the second trough line. By the time the third trough line passed no rain at all was falling.

### TEMPERATURE AND HUMIDITY

The passage of the wave had virtually no effect upon temperature. Temperature prior to the wave passage ranged from 57° F. to 61° F. and changes during wave passage did not exceed 1°.

Humidities were high at the approach of the wave, ranging from 90 to 100 percent. The high humidities may be ascribed to the fact that rain had been falling. Although there was a slight fall in humidity as the trough lines passed, it was usually less than 5 percent, and was probably due to the cessation of rain.

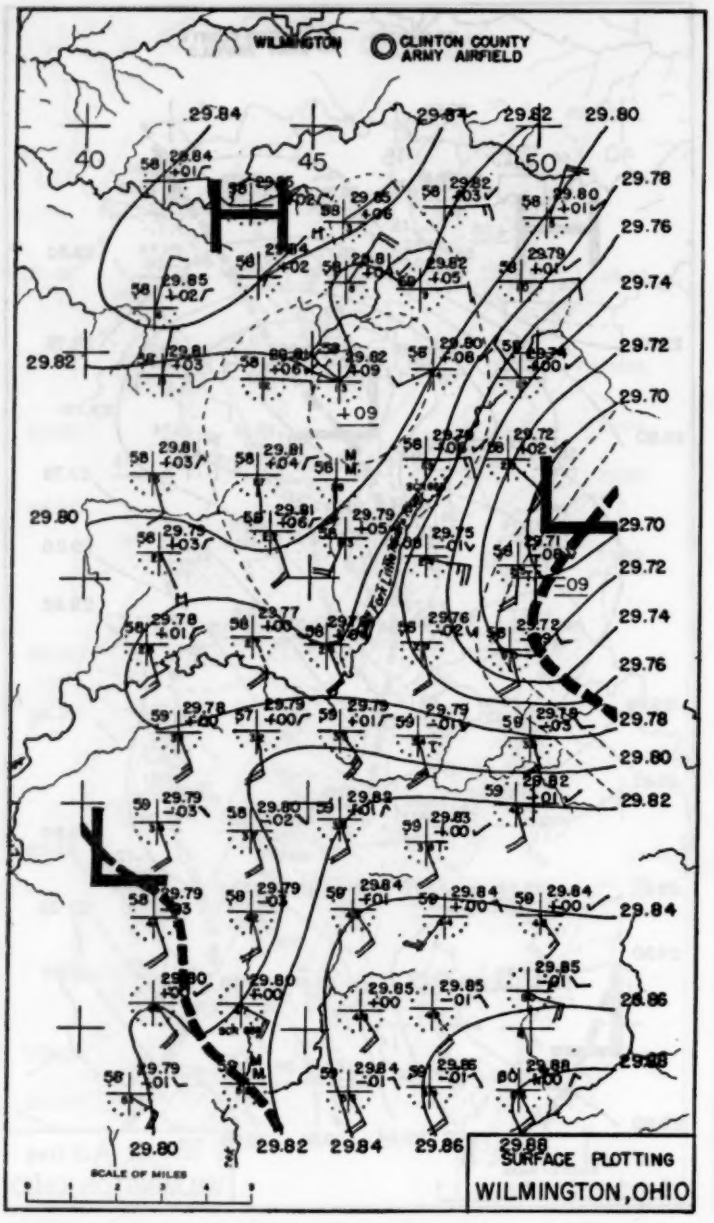


FIGURE 10.—Micro-synoptic chart for 1325 EST, April 7, 1948. The second trough line is almost entirely east of the network, while the third trough line is advancing slowly from the southwest.

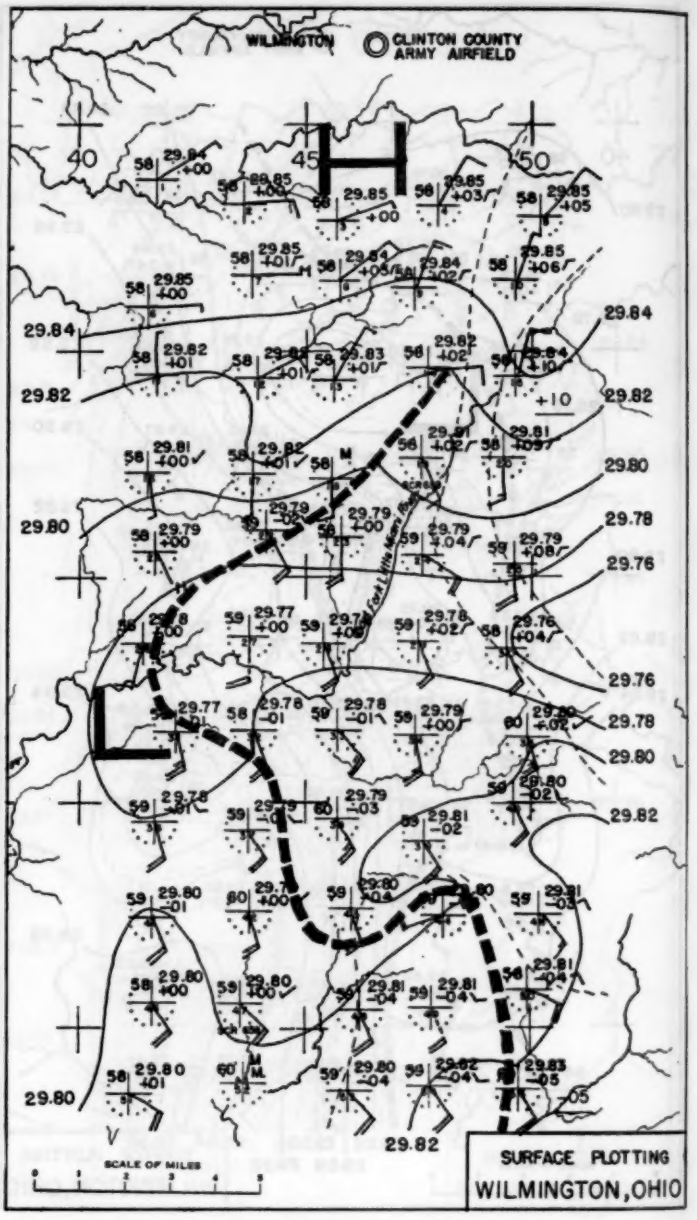


FIGURE 11.—Micro-synoptic chart for 1330 EST, April 7, 1948. The third trough line is now centered over the network.

## SYNOPTIC RELATIONSHIPS

The sectional synoptic chart for 1330 EST, April 7, 1948 (fig. 12), is approximately synchronous with the passage of the wave over the network. Although the wave had attained a depth of 29.71 inches (1006 mb.) at the time of the map, its existence is not apparent. Pressures at nearby Cincinnati and Columbus were 1011.2 and 1013.2 mb., respectively.

The depression wave may have been related to the squall line shown on the sectional chart. The 6-hourly reports of thunderstorms and rainfall indicate that the squall line was most intense along a line approximately from Terre Haute, Ind., to Pikeville, Ky. The pressure field surrounding the squall line indicates that it coincided with a pressure jump line, so we may infer that a pressure jump line coincided with its earlier positions, also. If we assumed that the maximum amplitude of the jump coincided with the maximum amount of rainfall, its position would have been in the vicinity of Terre Haute, possibly somewhat east and south of it. We are certain that the squall line was weak in the vicinity of the network, since no appreciable jump was recorded, and since only a small amount of rain fell.

From the above reasoning we conclude that in addition to the depression wave there was also a pressure jump. We also conclude that they did not achieve their maximum intensities at the same time, nor were their centers of maximum amplitude coincident with each other.

The author [6] has observed frequent combinations of pressure jumps and depression waves in which centers of maximum amplitude were offset from each other. In

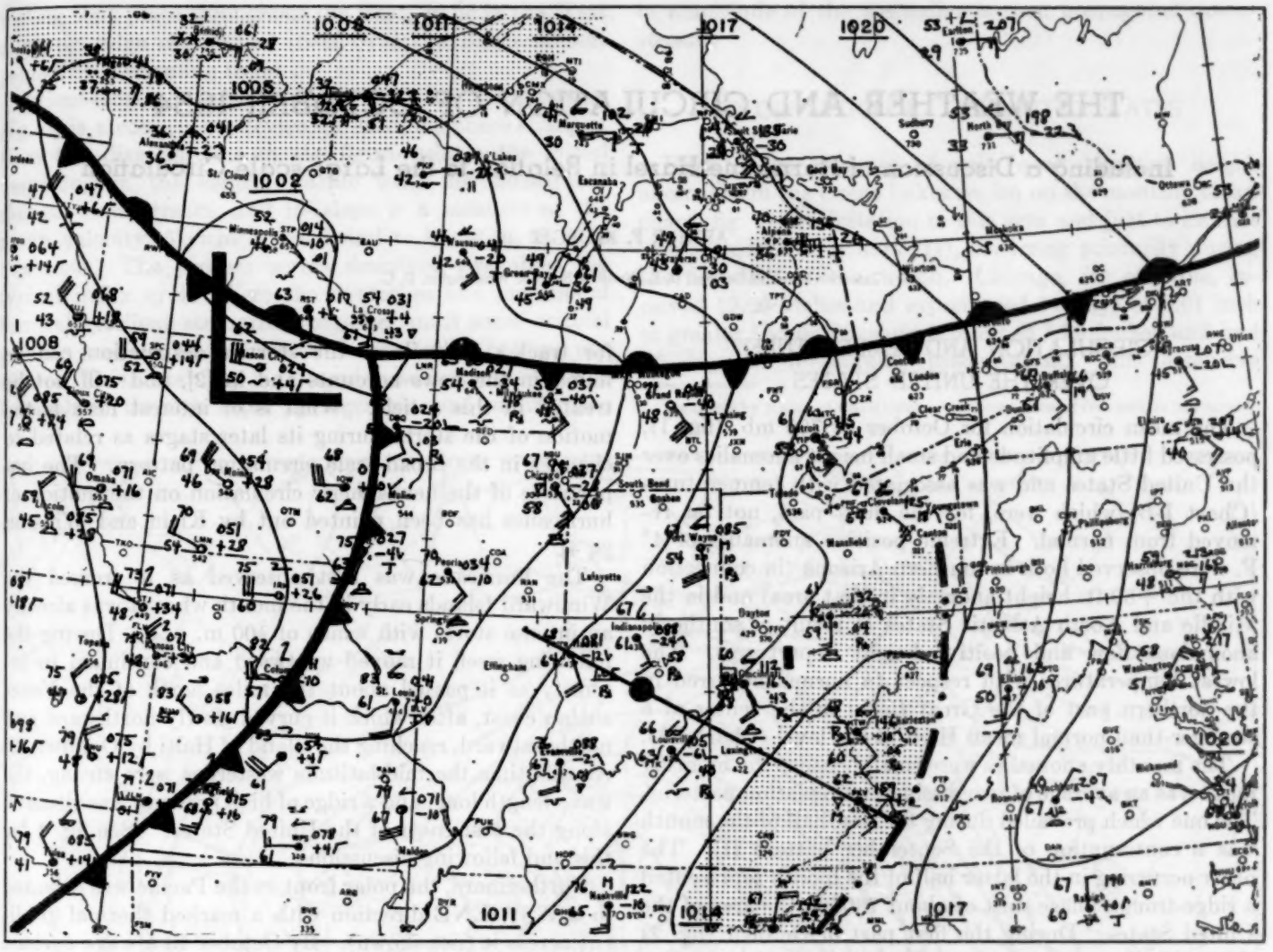


FIGURE 12.—Sectional synoptic chart for 1330 EST, April 7, 1948. A line has been drawn indicating the inferred line of maximum intensity of the squall line. The solid circle indicates the inferred center of maximum amplitude of the pressure jump. Location of the network is shown as a solid rectangle in southwestern Ohio.

some cases small, intense fields were completely offset from each other, so that some stations observed only the pressure jump, while others observed only the depression wave. The case presented is apparently in this category.

## CONCLUSION

The depression-type wave appears to be of minor importance so far as its immediate effect upon weather is concerned; but its overall importance may be vastly greater in its relationship to the pressure jump line. This relationship, the multiplicity of trough lines in the wave, the offset effect, and the possible role in the genesis of tornadoes leaves an interesting field for more detailed investigation.

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# THE WEATHER AND CIRCULATION OF OCTOBER 1954 [1]

## Including a Discussion of Hurricane Hazel in Relation to the Large-scale Circulation

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### CIRCULATION AND TEMPERATURE OVER THE UNITED STATES

The mean circulation for October at 700 mb. (fig. 1), possessed little amplitude and small height anomalies over the United States and was associated with temperatures (Chart I-B) which were, for the most part, not far removed from normal. Extreme positive anomalies of 4° F. were observed both in southern Arizona (in connection with the +80-ft. height anomaly in that area) and in the Middle and North Atlantic States (a result of southerly anomalous flow and positive height departures). The lowest temperatures with respect to normal occurred in the northern part of the Great Basin in the center of a stronger-than-normal mean High at sea level (Chart XI).

The monthly anomalies were small because the monthly mean was an average of two dissimilar circulation patterns. The one which prevailed during the first half of the month was a continuation of the September pattern [1]. The other occurring in the latter half of the month represented a ridge-trough phase shift of about 180° in the area of the United States. During the first part of October (fig. 2) the westerlies were stronger than normal with a ridge present over the East, a weak trough in the Northern Plains States and another off the Pacific Coast. This pattern was associated with above normal temperatures over most of the country and below normal only in the north and west (fig. 3). Some of the daily maximum temperatures during this period were: Greensboro, N. C., 95°; Columbia, S. C., 101°; Raleigh, N. C., 98°; Augusta, Ga., 97°; Washington, D. C., 93°; and Boston, Mass., 90°. During the last half month (fig. 2) the westerlies weakened and a ridge was established along the Pacific Coast accompanied by a trough in the East with a change to below normal temperatures over most of the country (fig. 3).

### CHANGES IN THE PLANETARY WAVE PATTERN AND THE MOTION OF HURRICANE HAZEL

The change in circulation occurred over a period of about a week near the middle of the month. During this week the eighth hurricane of the season, Hazel, lashed the island of Haiti, the Bahamas, and the eastern part of the United States and Canada. (See Chart X for track.) Details of the storm's destruction can be found in the news accounts and in [2], and will not be treated in this article. What is of interest here is the motion of the storm during its later stages as related to changes in the broad-scale circulation pattern. The importance of the hemispheric circulation on the motion of hurricanes has been pointed out by Klein and Winston [3, 4].

The hurricane was first observed as it crossed the Windward Islands early in the month when it was already an intense storm with winds of 100 m. p. h. During the following week it moved westward and continued to intensify as it passed about 100 miles north of the Venezuelan coast, after which it curved slowly northward and northeastward, reaching the island of Haiti by October 12. At this time the mid-latitude westerlies were strong, the wave-length long, and a ridge of high pressure was situated along the east coast of the United States. (See fig. 4 for this and following discussion.)

Furthermore, the polar front in the Pacific was oriented in a WSW-ENE direction with a marked thermal gradient across it (not shown). By October 13 a wave cyclone had formed near the Aleutians and the amplitude of the westerlies downstream began to increase. The cyclone continued to grow, acquiring on the 14th an intense circulation, while downstream heights continued to rise all along the Pacific coast and started to fall throughout the Central Plains. Hurricane Hazel meanwhile continued its northward motion curving toward the northwest as it was deflected by the strengthening ridge to its north. On the 15th the trough in the Plains States (and a surge of cold air with it) moved eastward accompanied by strong deepening over Lake Superior. Between this deepening trough and the stationary High off the Middle Atlantic coast the southerly flow intensified. Hazel under the influence of this steering current, was swept inland in the Carolinas and carried rapidly northward, acquiring not long afterwards the characteristics of an intense extratropical storm as the cold continental air to its west spiraled into its center. The hurricane center followed a track from the Carolinas, through Virginia, Maryland (passing through the western suburbs of Washington, D. C.), Pennsylvania, and New York into Canada, traversing this entire distance in some 12 hours. As it passed and the trough moved to the east coast, pronounced

[1] See Charts I-XV following p. 316 for analyzed climatological data for the month.

cooling took place throughout the East, while in the West a strong ridge established itself over the Basin accompanied by a warming trend.

A time-longitude section of daily 700-mb. height changes (fig. 5) is a convenient device for studying these changes. Here the diagonal line in the figure relates the initial deepening in the central Pacific with the subsequent changes downstream, and its slope is a measure of the group velocity [5], which was found to be 28 m. p. s. in this case. The process herein described resembles the typical index cycle where the westerlies and meridional thermal gradient strengthen together until some critical point is reached beyond which the westerlies become unstable. This instability is released in some portion of the hemisphere through rapid cyclogenesis, and an increase in amplitude of the westerlies is then propagated downstream.

## PRECIPITATION IN THE UNITED STATES

Despite the presence of only weak negative height anomalies in the Great Lakes region on the monthly mean chart (fig. 1) precipitation in this area and just to its east was considerable (Chart III), occurring primarily during the first half of the month. Chicago, for example, received 12.06 inches and experienced 14 days of 0.01 inch or greater,[2] while Pittsburgh received 7.79 inches and had 15 days of measurable precipitation. This extensive

[2] See article by Nash and Chamberlain on Chicago storm of Oct. 9–11, in this issue.

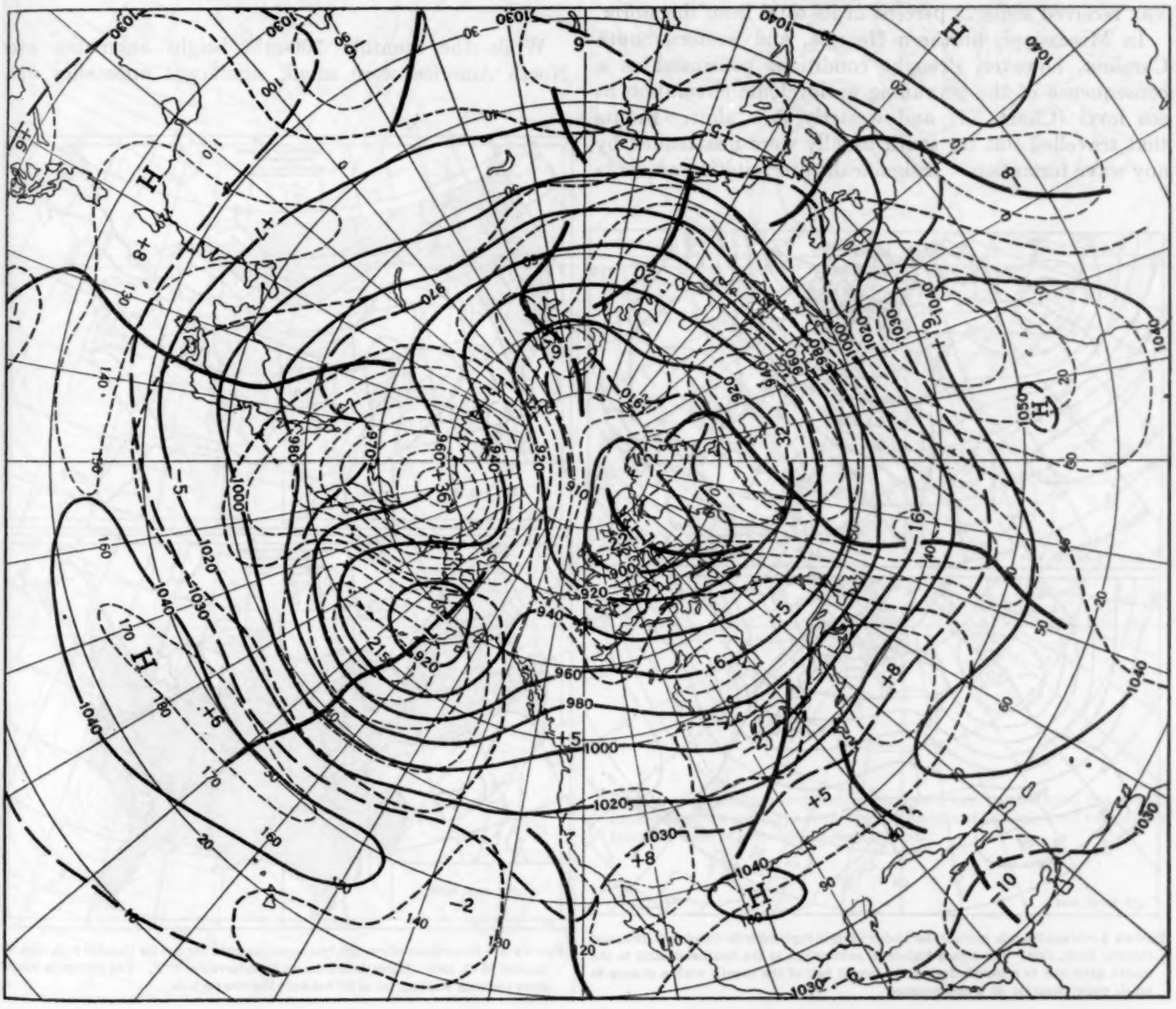

FIGURE 1.—Mean 700-mb. contours and height departures from normal (both in tens of feet) for October 2-31, 1954. Height anomalies were not far from normal over North America but quite large in the rest of the hemisphere.

precipitation was linked with the large number of days with fronts in the Central Plains and Lower Lakes region (fig. 6). During the first part of the month the fronts which pushed south across the Canadian border occasionally became quasi-stationary in the Lakes region, being unable to penetrate farther due to the strong high-level anticyclone in the Southeast. These fronts had pronounced thermal contrasts in the mid-troposphere and were associated with strong jets, but while overrunning and precipitation were frequently appreciable, wave formation was weak.

The large precipitation amounts in the Carolinas and Virginia were largely due to the hurricane, which provided the first soaking rains in months for much of these drought-stricken States. It gave Charleston, S. C., for example 88 percent of its monthly rainfall total, while Roanoke, Va., received some 73 percent of its total from the storm.

In Mississippi, northern Georgia, and western South Carolina, however, drought conditions continued as a consequence of the prevailing anticyclonic circulation at sea level (Chart XI) and westerly flow aloft. Fronts that travelled this far south usually were unattended by any wave formation. Insignificant precipitation amounts similarly occurred west of the Rockies in connection with the Basin High and above normal heights at 700 mb.

Most of the heavy rainfall in southeastern Texas was associated with a weak, tropical disturbance which moved inland from the Gulf of Mexico on October 5, and gave amounts as great as 6 inches in 6 hours in Brownsville. This disturbance weakened as it curved around the subtropical High cell into southeastern New Mexico, while at the same time cold air moved in from the northeast at lower levels and banked against the mountains. The resulting rainfall over the eastern slopes of the Rockies in New Mexico was copious and caused flash floods in the Pecos River and its tributaries.

## CIRCULATION FEATURES IN OTHER PARTS OF THE HEMISPHERE

While the monthly 700-mb. height anomalies over North America were small, significant anomalies were

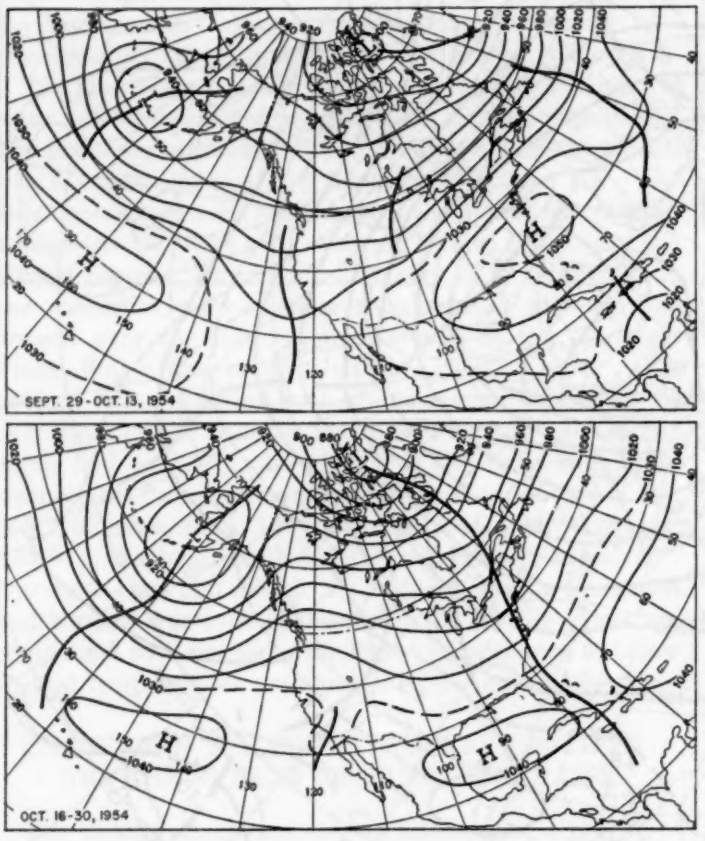


FIGURE 2.—Mean 700-mb. contours for 15-day periods September 29–October 13, 1954, and October 16–30, 1954. The strong high-level anticyclone in the Southeast early in the month gave way to a trough during the second half of the month with a change to much cooler weather as a consequence.

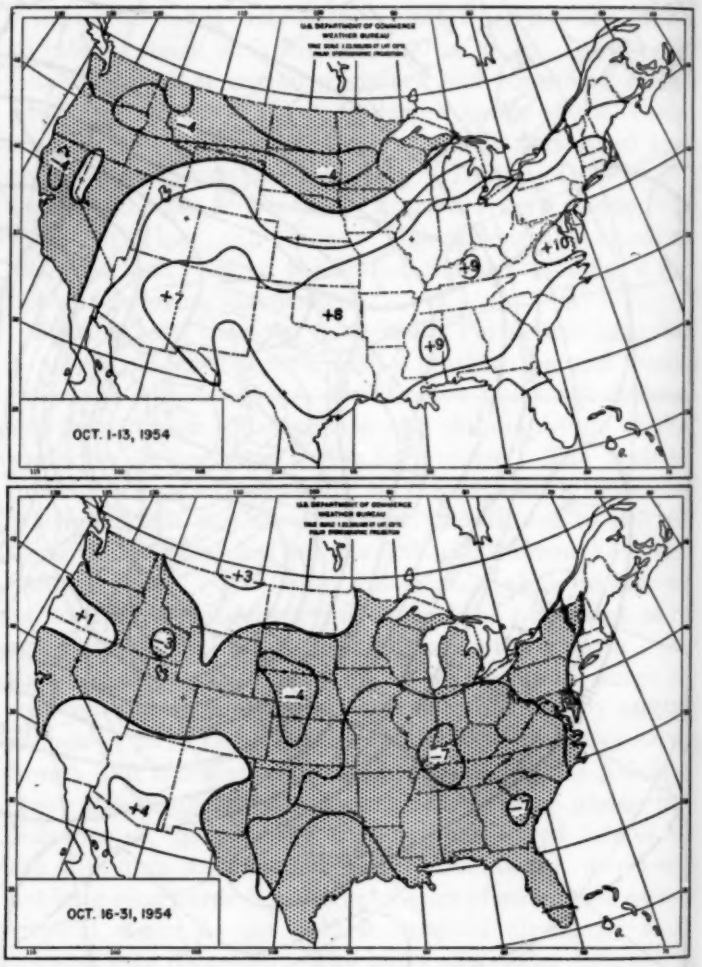


FIGURE 3.—Departures of average temperatures from normal for October 1–13, 1954, and October 16–31, 1954. Isopleths are drawn for intervals of 3° F. The change in temperature anomaly was as great as 16° between the two periods.

present over other parts of the hemisphere. The largest was that over northeastern Siberia where heights were 350 ft. above normal. This anomaly was established early in the month when a blocking ridge retrograded from Alaska and stabilized itself in the region. To its southeast the Aleutian Low and central Pacific trough were well developed with heights 200 ft. below normal. Strong northerly flow to the west transported considerable cold air into the central Pacific, bringing about a marked cooling from September and a strengthening of the north-south thermal gradient. Along this thermal contrast frequent cyclogenesis took place, with most of the storms moving into the Gulf of Alaska and then decaying.

In the central and northern Atlantic intense storminess was associated with a mean trough and heights depressed as much as 320 ft. from the normal. On the other hand the eastern Atlantic and southwestern Europe continued to experience above-normal heights as the Azores High

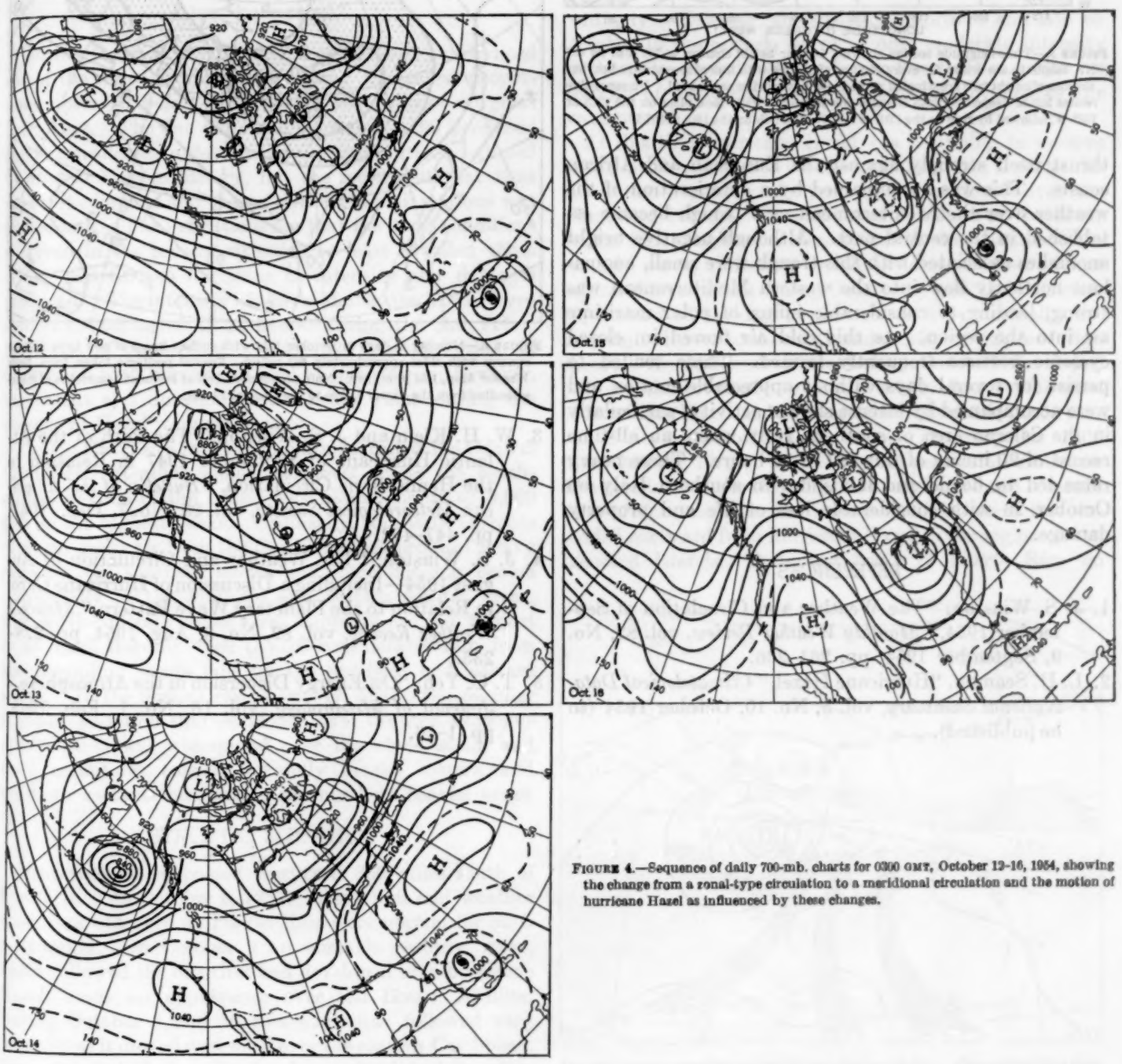


FIGURE 4.—Sequence of daily 700-mb. charts for 0300 GMT, October 12-16, 1954, showing the change from a zonal-type circulation to a meridional circulation and the motion of hurricane Hazel as influenced by these changes.

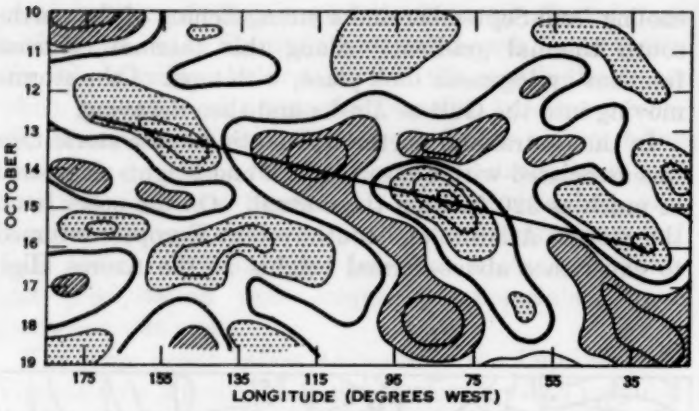


FIGURE 5.—Time-longitude section showing 24-hour height changes at 700 mb. for 45° N. Isopleths are drawn for every 200 feet of change with line of zero change heavier. Regions of height falls are stippled while those having rises are shaded. Diagonal line relates initial deepening with changes downstream. Falls took place on the 12th at 155° W. followed by rises on the 13th at 110° W. and falls on the 14th at 80° W.

thrust itself strongly against the European and African coasts. This was accompanied by a deterioration of the weather over the Mediterranean as a trough became established in the central part. Although negative height anomalies associated with this trough were small, anomalous northerly flow into the western Mediterranean was strong, leading to considerable influx of polar maritime air into the region. As this cold air flowed in, closed cyclonic vortices frequently formed. These tended to persist for several days without appreciable motion and were accompanied by intense shower activity, particularly in the Salerno area of southern Italy where an all-time record of 20 inches of rain fell in 15 hours. These heavy rains led to floods and landslides in southern Italy on October 26 with considerable loss of life and property damage.

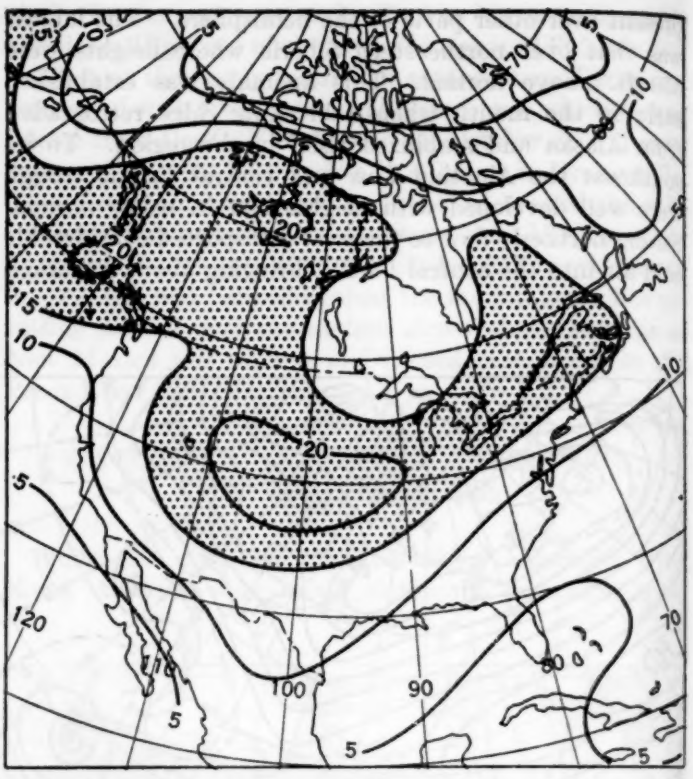

FIGURE 6.—Number of days in October 1954 with surface fronts of any type (within squares with sides approximately 500 miles). Frontal positions taken from *Daily Weather Map*, 1:30 p. m. EST. Note pronounced belt of frequent occurrence of fronts extending from the Lower Lakes to the Central Plains.

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# SEVERE FLOODS OF OCTOBER 12-15, 1954 IN PUERTO RICO

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## INTRODUCTION

During October 12–15, 1954, Puerto Rico experienced one of the worst floods in its history. It reached proportions observed before only during the passage of great hurricanes. The San Ciriaco hurricane of 1899 produced floods considered to date to be the most intense suffered by Puerto Rico in history, but the records at that time were not complete and the network of rainfall stations was inadequate. The indications are that the flood conditions observed in the present situation at least equalled those of the San Ciriaco hurricane in intensity and damages produced. The intensity of the rainfall at the Toro Negro station (28.00 inches in 24 hours) during the San Felipe hurricane of September 13–14, 1928 exceeded that in connection with hurricane Hazel at this station; however, the extent and duration of the heavy rains during the passage of Hazel were greater.

Puerto Rico has a range of mountains, called the Central Cordillera, extending almost east-west across the south-central portion of the Island with elevations up to 5,000 feet on the highest peaks. Ordinarily, southerly currents of warm moist air from the Caribbean Sea produce heavy rains on the southern slopes and some flooding occurs occasionally in the southern and eastern coastal areas. The north-central coastal areas normally are not subject to as much flooding even though considerable rain from the prevailing winds falls on the northern and eastern slopes. In the present case, however, due to the peculiar synoptic situation that developed over the area, excessive precipitation was widespread over the whole island and flood conditions ensued not only in the eastern and southern sections but also in the northern coastal areas.

## SYNOPTIC SITUATION

Hurricane Hazel passed westward 350 miles south of Puerto Rico on October 6, 1954. The winds and weather conditions observed at Puerto Rico were normal for such a situation. On October 9 an unstable easterly wave, which followed the one that had developed into hurricane Hazel, made its appearance over the Lesser Antilles. During October 9 and 10 this wave was followed very carefully as it moved westward over the eastern Caribbean. For a time it looked as if a development might take place on this wave and all interested agencies were alerted accordingly. However, the situation improved and late on October 10 the easterly wave, of only moderate intensity at the time, passed westward over Puerto Rico. Shower activity of moderate to heavy intensity prevailed as the wave passed.

At this time hurricane Hazel was beginning to recurve to the north-northeast over the Caribbean and a particular circulation began to take form in the low levels over the Windward Islands. The winds at San Juan in the lower 10,000 feet, which were easterly before the passage of the easterly wave, shifted to southeast and south-southeast behind the wave, but during October 11 and early October 12, instead of backing to the east as they normally do, they shifted more to the south and persisted with moderate speeds. An east-west oriented shear line had developed between the southerly to southwesterly flow to the east of hurricane Hazel and the easterly trades which still prevailed northward of Puerto Rico. The map for 1800 GMT, October 12 (fig. 1), shows this particular situation. The positions of the shear line 24 hours before and after the time of the map also are indicated. The shear line extended eastward from hurricane Hazel to the region of the Leeward Islands. It moved north of Puerto Rico on

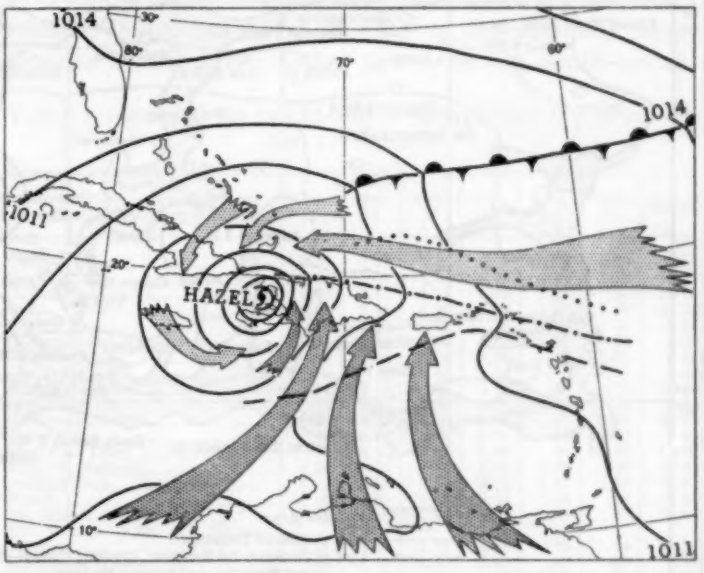


FIGURE 1.—Surface weather map for 1800 GMT, October 12, 1954. The position of the shear line is shown for 1800 GMT on October 11 (dashed line), October 12 (dot dashed line) and October 13 (dotted line). Large arrows show main air currents.

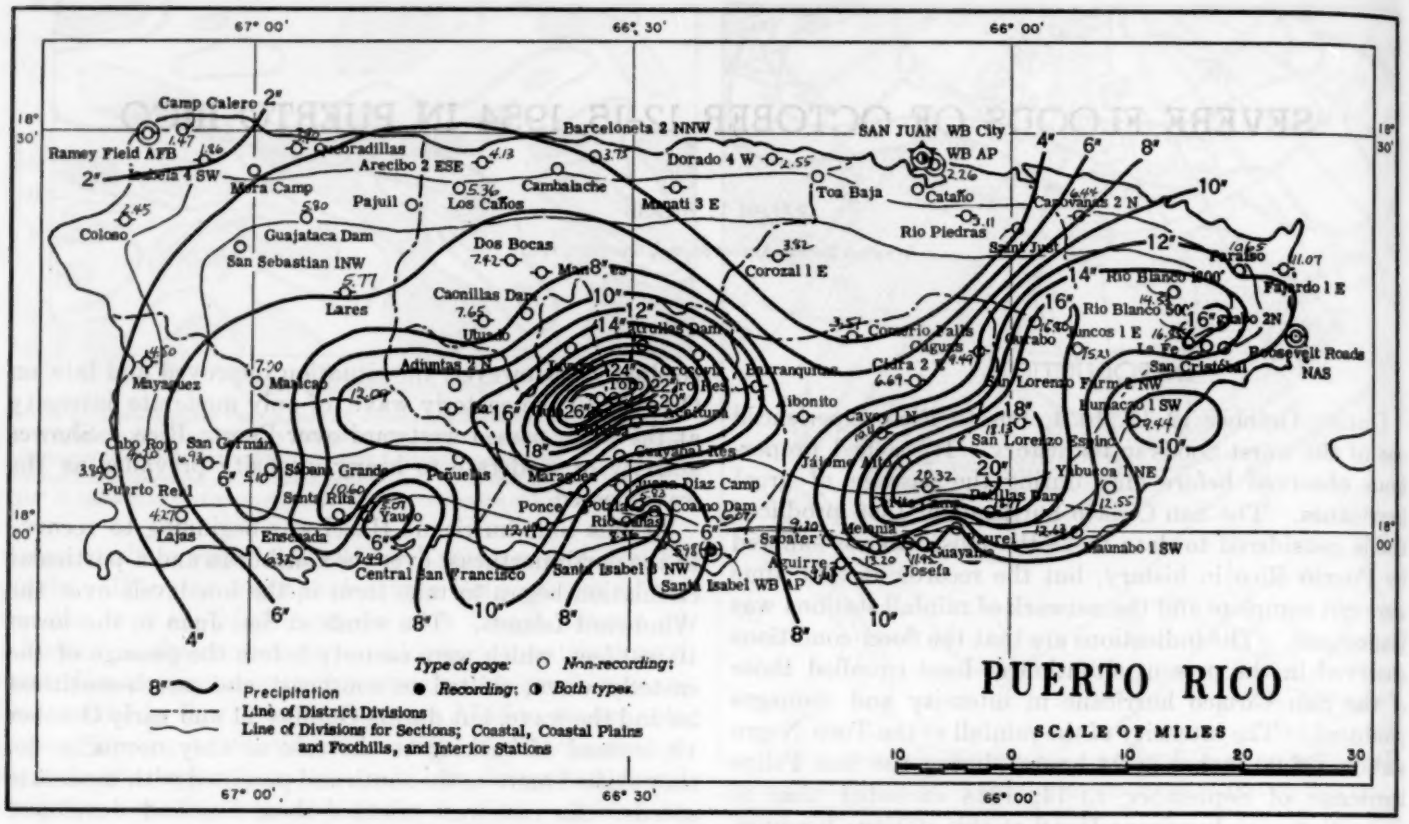


FIGURE 2.—Rainfall distribution over Puerto Rico for the period October 11-16, 1954. Amounts are in inches.

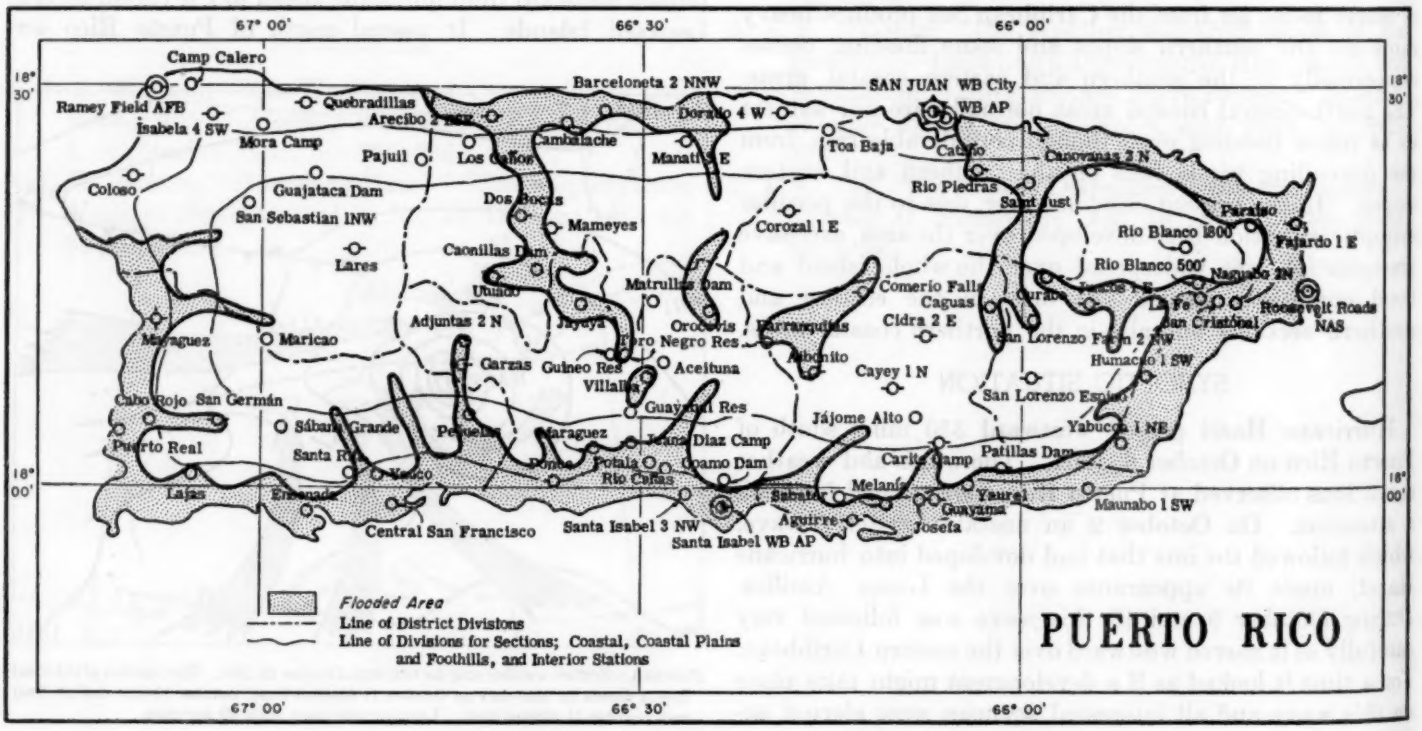


FIGURE 3.—Areas of Puerto Rico subjected to floods during October 12-15, 1954, are indicated by stippling.

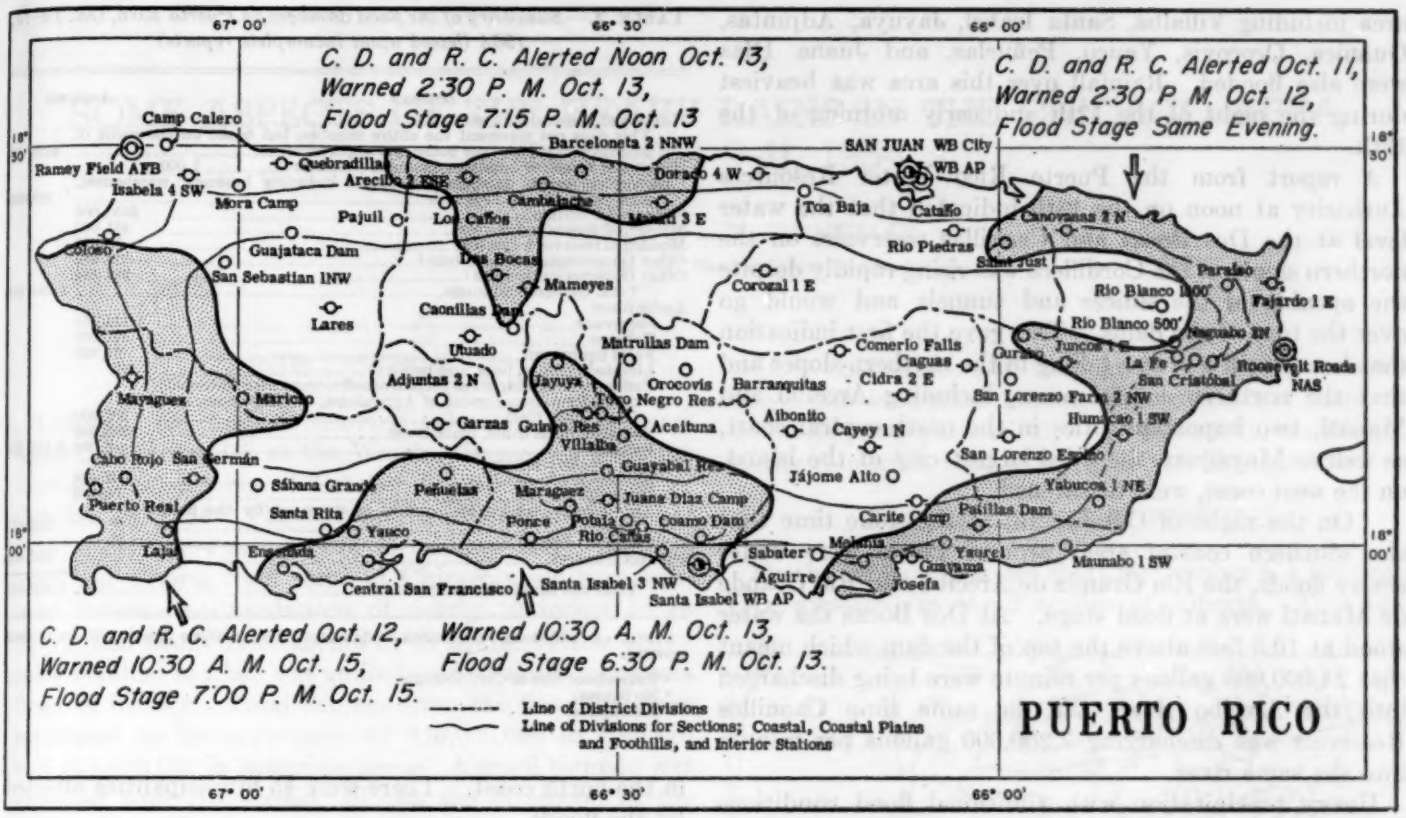


FIGURE 4.—Area of Puerto Rico covered by flood warnings are indicated by stippling. Times of issue of warnings, times of alerting Civil Defense (CD) and Red Cross (RC) and times rivers were at flood stage are indicated.

October 12 and persisted in the area until Hazel moved northward out of the region on October 14. Strong southerly flow prevailed over Puerto Rico until October 15. The radiosonde ascents at San Juan during the period showed this air to be saturated up to the 500-mb. level. The strong convergence and instability present in the area due to the effect of this shear line combined with the orographic effect on the southern slopes of Puerto Rico produced torrential rains of extraordinary intensity and duration.

## RAINFALL AND FLOODS

Rains previous to October 11 which occurred in connection with the easterly wave described, saturated the soil and caused a high percentage of runoff. Thus the excessive precipitation which started on October 12 flowed immediately into the rivers and reservoirs and severe floods followed. The intensity of the rainfall is indicated by such observations as that at Toro Negro Dam where 26.07 inches fell during the period October 11–16. Figure 2 shows the rainfall distribution for October 11–16 and table 1 gives a breakdown by 24-hour periods for October 11 through 16.

Figure 3 shows the areas subjected to floods during October 12–15. The eastern coastal areas from Carolina-Fajardo to Salinas including Humacao, Maunabo, Naguabo, Las Piedras, Yabucoa, and Guayama, suffered severe floods on October 12. This area had already received copious rainfall from the easterly wave. The next day, October 13, the rivers in the area from Santa Isabel to Guànica began to rise and by late afternoon and early evening Ponce had 6 feet of water in the streets in some sections of the city. Other towns in the south-central

TABLE 1.—*Rainfall for the 24-hour periods ending at 6 p. m.* AST, *Oct. 11–16, 1954*

| Puerto Rico Water Resources Authority reporting stations | Oct. 11 | Oct. 12 | Oct. 13 | Oct. 14 | Oct. 15 | Oct. 16 | Total |
|---|---|---|---|---|---|---|---|
| Caonillas Dam | 0.37 | 0.27 | 8.30 | 0.50 | 0.20 | 0.00 | 9.64 |
| Carite Dam | 1.82 | 3.01 | 4.84 | 3.66 | 2.42 | 1.52 | 17.27 |
| Carite Plant No. 1 | 3.65 | 2.67 | 4.71 | 5.53 | 2.27 | .93 | 19.76 |
| Carite Tunnel | 3.60 | 2.78 | 4.00 | 5.05 | 3.61 | 1.28 | 20.32 |
| Coamo Dam | .64 | 2.00 | 1.19 | .83 | 1.26 | .15 | 6.07 |
| Colonia Sabater (Salinas) | 1.15 | 1.60 | .50 | 3.85 | 1.80 | .30 | 9.20 |
| Comerio Falls | .89 | .48 | 1.04 | 1.00 | .08 | .02 | 3.51 |
| Dos Bocas | 0.00 | .27 | 5.85 | .10 | .03 | .58 | 7.42 |
| Guayabal Reservoir | 1.15 | 2.10 | 3.40 | 2.79 | .55 | .05 | 10.04 |
| Guayama | 1.98 | 2.92 | 3.47 | 1.76 | 1.90 | .72 | 12.75 |
| Guineo Reservoir | 1.13 | 4.90 | 12.05 | 5.05 | .41 | 0.00 | 23.54 |
| Juana Díaz | 1.20 | .76 | 3.66 | 2.11 | .46 | 0.00 | 8.19 |
| Matrullas Dam | .78 | 3.80 | 10.45 | 1.09 | .05 | 1.42 | 17.59 |
| Melania (Salinas) | 2.30 | 1.75 | 4.15 | 2.40 | 2.25 | .35 | 13.20 |
| Patillas Dam | 5.47 | 2.86 | 5.37 | 2.18 | 1.81 | 1.08 | 18.77 |
| Ponce | 1.90 | .68 | 6.47 | 2.54 | .48 | .40 | 12.47 |
| Río Blanco (500 ft.) | 2.95 | 3.38 | 3.04 | 1.93 | 1.18 | .57 | 13.05 |
| Río Blanco (1,800 ft.) (Hicaco Dam) | 3.20 | 3.65 | 3.33 | 2.88 | .53 | .94 | 14.53 |
| Río Canas (Juana Díaz) | .52 | 1.85 | 2.89 | 2.25 | .79 | .06 | 8.36 |
| Río Jueyes (Salinas) | 2.74 | 1.96 | .91 | 2.42 | 1.00 | .15 | 9.18 |
| Toro Negro Plant No. 1 | .92 | 1.85 | 6.50 | 2.87 | 1.94 | .06 | 14.14 |
| Toro Negro Tunnel | .90 | 6.37 | 13.50 | 4.98 | .32 | 0.00 | 26.07 |
| Yauco | ..... | .80 | 2.80 | 1.32 | ..... | .15 | 5.07 |
| Yaurel Flume (Arroyo) | 3.50 | 2.40 | 2.25 | 1.25 | 1.66 | .90 | 11.96 |

area including Villalba, Santa Isabel, Jayuya, Adjuntas, Guánica, Orocovis, Yauco, Peñuelas, and Juana Díaz were also flooded. Rainfall over this area was heaviest during the night of the 12th and early morning of the 13th.

A report from the Puerto Rico Water Resources Authority at noon on the 13th indicated that the water level at the Dos Bocas and Caonillas reservoirs on the northern slopes of the Cordillera was rising rapidly despite the opening of the sluices and tunnels and would go over the tops of the dams. This gave the first indication that heavy rain was also falling in the northern slopes and that the northern coastal areas, including Arecibo and Manatí, two important cities in the north-central coast, as well as Mayaguez, the third largest city of the island, on the west coast, were threatened.

On the night of October 13, at the same time that the southern coastal areas around Ponce were under severe floods, the Río Grande de Arecíbo and Río Grande de Manatí were at flood stage. At Dos Bocas the water stood at 10.5 feet above the top of the dam which meant that 24,000,000 gallons per minute were being discharged into the Arecibo river. At the same time Caonillas Reservoir was discharging 7,200,000 gallons per minute into the same river.

Heavy precipitation with additional flood conditions and damage to property persisted, specially in the southern slopes until October 15, when the situation finally abated.

## FLOOD DAMAGES

There were nine persons killed; eight by drowning and one by a landslide.

Damage to agriculture, livestock, homes, businesses, highways, bridges, municipal street and sewer systems, personal property losses (including homes destroyed and damaged) will exceed all previous floods since 1899. Reports of damages are slow coming in, and from many areas the reports of the total damages (all kinds) are incomplete. For example, one warehouse at Mayaguez reported a loss of $85,000 due to flooding, yet the official report from that area showed total damages of only $60,000. The official reports are underestimates because either the people fail to report promptly to the appropriate authority, or their reports fail to cover damages for rural and urban as well as metropolitan districts. A summary of the flood damages based upon incomplete reports is given in table 2.

It is significant to note that more than 550 houses were destroyed and about 1,000 (estimated) were damaged. Ponce bore the brunt of houses destroyed with 253. No mention is made of the houses destroyed or damaged in the rural areas.

Some 11,000 people were successfully evacuated by the Civil Defense and Red Cross in the inundated areas. Helicopters of the U. S. Air Force from Ramey Field assisted in taking the people out of the flooded sections in the north coast. There were 45 municipalities affected by the floods.

TABLE 2.—*Summary of the flood damages in Puerto Rico, Oct. 12–15, 1954 (based upon incomplete reports)*

| *Damages* | | *Amounts* |
|---|---|---|
| Number of houses destroyed | 555 | |
| This does not represent the entire number, but based on the value of approximately $1,000 per house and appurtenances | | $555,000 |
| Number of houses or buildings damaged (estimated) | 1,000 | |
| Incomplete report; damages (all kinds) including business, warehouses, sugar mills, etc., at $200 each | | 200,000 |
| State roads, bridges | $650,000 | |
| Municipal streets and sewers | 451,000 | |
| Municipal reserves for repair | 15,459 | |
| Other Government organizations [1] | 302,533 | |
| Other Government entities [1] | 212,494 | |
| Total Government losses | | 1,631,486 |
| Agriculture: | | |
| Sugarcane | 1,154,854 | |
| Tobacco | 317,500 | |
| Farm equipment | 24,850 | |
| Livestock (cattle, hogs, and poultry) | [2] | |
| Coffee (in some districts 80 percent of coffee crops were destroyed; taken from Department of Agriculture, Civil Defense, and Land Office files) | 400,000 | |
| Bananas, citrus fruits, truck crops | 295,000 | |
| Pastures | 6,000 | 2,198,204 |
| Personal property losses: | | |
| Household effects | 299,448 | |
| Domestic animals | [3] 6,203 | |
| Automobiles, trucks, etc., ruined or damaged by the flood waters | [2] | 305,651 |
| Hydroelectric dams | [2] | |
| Indirect damages | | 155,000 |
| Total loss based on incomplete data | | 5,045,341 |

NOTE.—As additional information on damages filters in these figures will be revised upward.

[1] Taken from files of Civil Defense.
[2] No figures.
[3] Incomplete.

## WARNING SERVICE

The warnings were timely and adequate. On the night of October 11 the Civil Defense and Red Cross were alerted to the possible danger of floods through the Island. The Civil Defense and Red Cross had been alerted on the night of the 10th to the possible development of a disturbance on the easterly wave previously noted, and remained on the alert through the flood threat. It was due to the work of evacuation, housing, and feeding of people by these two organizations that greater loss of life was averted. All available communication means were used to disseminate the warnings to the people. The Puerto Rico Association of Radio Broadcast Stations carried the warnings to threatened areas every half hour. State Police Radio alerted every police precinct on the Island and the Puerto Rican Amateur Net not only disseminated the warnings, but collected rainfall observations from important locations. A map indicating the areas covered by the warnings, with the time of issue, times the rivers were at flood stage, and time of alerting cognizant authorities, is shown in figure 4.

The cooperation and assistance rendered this Weather Bureau office by the Puerto Rico Water Resources Authority in providing information on the intensity of the rainfall, regular rainfall observations, and the height of the water level in the reservoirs, was of inestimable value in determining the duration and extent of the floods.

# SOME ASPECTS OF THE HEAVY RAINS IN THE CHICAGO AREA, OCTOBER 9–11, 1954

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## INTRODUCTION

Chicago, Ill., had its heaviest rainstorm in 69 years when 5.63 inches fell at the Weather Bureau in 24 hours between the evening of October 9, and the evening of October 10, 1954. The 6.72 inches in 48 hours, October 9–11, 1954 set a new record for that period. Reliable unofficial reports from some of Chicago's southern suburbs indicate accumulations of nearly 10 inches in 30 hours, and about 12.50 inches in 48 hours. These heavy rains resulted in what was undoubtedly Chicago's greatest flood in history. Total damage from the flood has been estimated to be approximately $10,000,000 in Chicago and $15,000,000 in suburban areas. A small tornado was reported near Homewood, Ill., on the afternoon of the 10th. Homewood is 10 miles southwest of Chicago's city limits. (c. f. Brunk [1], especially for additional information on the flooding and flood damage.)

Although the most noteworthy rains fell over northern sections of Illinois and Indiana, heavy rains also fell during the period over southern sections of Michigan and Wisconsin, northwestern Ohio, and over eastern Iowa and northeastern Missouri. Storm rainfall for the entire rain area in the United States is shown in figure 1. This is based on measurements at first-order Weather Bureau stations only. After the excessive rains in the Chicago area, a special appeal to the general public was made by the Chicago Weather Bureau Office for all available rainfall measurements. Table 1 contains the rainfall measurements received in response to this request. These measurements supplement those published in the Chicago *Local Climatological Data* and in the Illinois *Climatological Data* for October 1954. Figure 2 is an isohyetal map for October 9–11 in the Chicago area.

This heavy rain situation is of particular interest not only because of the tremendous damage which resulted but because the reasons for the occurrence of rainfall of this intensity and duration are not obvious without a careful and detailed scrutiny of weather data available before and during the storm.

Indicative of the vertical motions which must have been present is the fact that almost all of the precipitation resulted from thunderstorm activity. Most of this thunderstorm activity occurred south of a front which was in the vicinity of Chicago at the time of the initial onset of precipitation.

It is the purpose of this article to examine certain causal and influential factors, and to evaluate them, for the most part, qualitatively. In this study, we are primarily concerned with the rains in the Chicago area.

## GENERAL SYNOPTIC FEATURES

On the 0030 GMT surface chart for October 8, a 1001-mb. Low appeared in the Province of Alberta. This Low

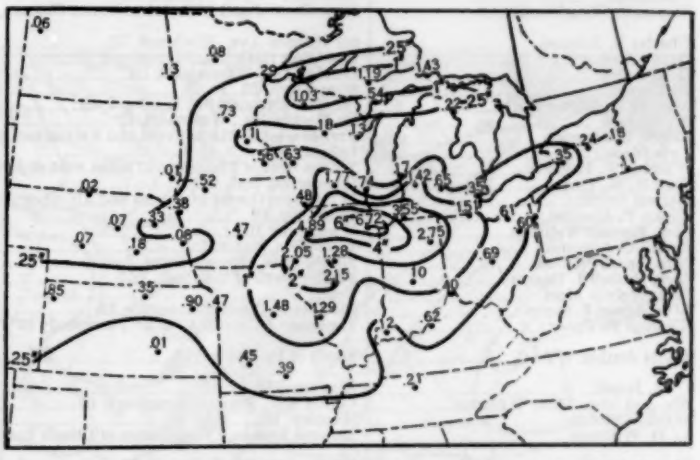

FIGURE 1.—Rainfall 0030 GMT, October 10 to 0030 GMT, October 12, 1954, for first-order Weather Bureau stations in the United States affected by the Chicago storm. Isohyets are labeled in inches.

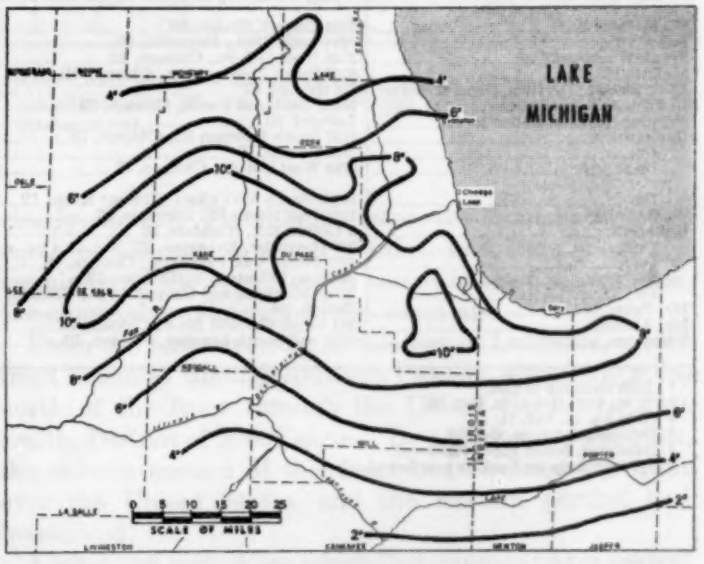


FIGURE 2.—48-hour rainfall, October 9-11, 1954, in Chicago area (after Brunk [1]).

TABLE 1.—*Special rainfall measurements in the Chicago area, Oct. 9–11, 1954*

[Amounts of rainfall are for the entire duration of the storm unless otherwise noted]

| Observer | Location of gage | Amount of rainfall | Type of gage |
|---|---|---|---|
| Leonard J. Spyer | 117 South Elm St., Mount Prospect, Ill. | 5.52 | Recording rain gage. |
| Charles Ferls, Jr. | 3247 Grand Blvd., Brookfield, Ill. | 7.04 | Green type, 8-inch capacity. |
| Edward R. Conrad | 7008 West 114th St., Worth, Ill. | 5.90 | Pail. |
| Wesley E. Hackett | 10445 South Prospect Ave., Chicago, Ill. | 8.97 | Plastic, 5-inch capacity. |
| Charles Eggersted | 3941 South Grove Ave., Stickney, Ill. | 7.20 | 6-inch capacity. |
| Mrs. F. van der Werff | 3649 Randolph, Lansing, Ill. | (1) | 10-quart pail. |
| Mrs. W. E. Hardie | 2649 Ashway Ave., Evanston, Ill. | 9.75 | Waste basket (no dimensions). |
| Norman Fisher | 3832 Franklin, Western Springs, Ill. | 7.30 | Unknown. |
| R. C. Jenkins | 6003 Woodward Ave., Downers Grove, Ill. | 7.02 | Victor rain gage. |
| Judy Jay | 207 North Elm, Hinsdale, Ill. | 11.12 | School-constructed gage. |
| Ralph Burlingame | 312 Brownell, Thornton, Ill. | 10.75 | Cement barrel. |
| R. T. Fischer | Warrenville, Ill. | 7.00 | Amateur gage. |
| Truex N. Upchurch | 1910 Hanover Lane, Homewood, Ill. | 10.30 | Cylindrical container. |
| C. W. Schelling | 1 mile north of Eola, Ill. | 10.00 | Unknown. |
| Mrs. John H. Beck | Warrenville, Ill. | 10.50 | Do. |
| Mrs. S. K. Landak | 7749 Langley Ave., Chicago, Ill. | [2] 2.20 | Do. |
| Mrs. Frances Meilleur | 9646 South 55th Ave., Oak Lawn, Ill. | 8.80 | Do. |
| J. M. Burgin | 1½ miles east of Rd. 59, ½ mile south of Geneva Rd. | 5.55 | Do. |
| Roy M. Nordine | The Morton Arboretum, Lisle, Ill. | 7.37 | Standard Friez. |
| N. F. Davis | 730 North Quinteur Rd., Palatine, Ill. | [3] 3.70 | Coffee can. |
| Unknown | 2923 North Albany Ave., Chicago, Ill. | 5.20 | Can. |
| John White | 2½ miles west of Campana factory, northwest of Batavia. | 8.20 | Unknown. |
| George C. Beck | 3540 Gunderson Ave., Berwyn, Ill. | 7.98 | Clint Youle. |
| Mrs. Charlotte Pierson | 5509 North Nottingham Ave., Chicago, Ill. | 6.25 | Round bucket. |
| C. Luebke | 3510 West Potomac Ave., Chicago, Ill. | 7.50 | 55-gallon, open-head drum. |
| Mrs. R. Whitecotton | 653 West Rd., Lombard, Ill. | 6.25 | Straight-sided scrub bucket. |
| A. F. Ochtman | 88th Ave. and 124th St., Palos Park, Ill. | 8.00 | Unknown. |
| L. E. Smith | International Harvester Farm, Hinsdale, Ill. (experimental farm, 2 miles south of Hinsdale, Ill.). | 6.45 | Homemade Friez type. |
| Unknown | 109th and Peoria, Chicago, Ill. | [4] 7.40 | Unknown. |
| Eugene J. Wenglowski | Near Central and Milwaukee Aves., Chicago, Ill. | 6.51 | Do. |
| Charles B. Johnson | 601 Hillside Ave., Elmhurst, Ill. | [5] 6.25 | 6-inch gage. |
| G. W. Becker | 2110 West 120th Pl., Blue Island, Ill. | 11.05 | Small plastic. |
| C. L. Jones | Landon Dr., Warrenville, Ill. | 7.00 | Unknown. |
| Unknown | Glen Ellyn, Ill. | 6.15 | Do. |
| Mrs. F. G. Wildermuth | 767 East Division St., Lombard, Ill. | 9.50 | Bucket. |
| M. Matson | 521 Roslyn Rd., Westmont, Ill. | [6] 12.50 | Tar bucket. |
| Ernest L. Munter | 8 miles west of Medaryville and 3 miles east of Gifford, Ind. | [7] 1.51 | Unknown. |
| Lyle Olson | Leland, Ill. | [8] 11.30 | Homemade gage. |
| William W. Hograve | 2 miles west of Plano and 17 miles west of Aurora, Ill. | 9.50 | Unknown. |
| Fred E. H. Trowe | Chesterton, Ind. | 7.31 | Homemade gage. |
| Vernell Smith | 17 miles northwest of Aurora and 3½ miles south of Elburn, Ill. | 8.25 | 17½-inch metal bushel basket. |
| Glenn T. Koerner | Coal City, Ill. | 3.50 | "Official" gage. |
| Mrs. Bernice Wellman | Wauconda, Ill. | [9] 5.50 | Boat. |
| David C. Johnston | Alfred St., Porter, Ind. | 8.80 | Unknown. |
| Mrs. Lewis Nichols | 230 Wells St., Crown Point, Ind. | 7.80 | Standard type. |
| Mrs. Russell J. Carson | 5 miles north of Wanatah, Ind. | 7.25 | Unknown. |
| Mrs. Melvin Most | Crete, Ill. | 8.75 | 12-inch pail. |
| Mrs. Anton J. Senty | 954 Sylvan Circle, Naperville, Ill. | 9.00 | Unknown. |
| Thomas B. Casey | Location: Latitude 41°37'33", longitude 87°57'03" | 9.45 | Recording rain gage of Illinois Division of Waterways. |
| Radio Station WTAQ | South of La Grange, Ill. | 5.00 | Unknown. |
| C. B. Jewell | Manteno, Ill. | 5.40 | Do. |
| Mr. and Mrs. Thos. Williams | Center Rd., Route 1, Frankfort, Ill. | 9.25 | Do. |
| William Hubbe | Huntley, Ill. | 3.20 | Graduated glass tube. |
| L. D. Williams | Armour Research Foundation of Illinois Institute of Technology, Lafox, Ill. | 11.20 | Rain and snow gage purchased from Standard Science Supply Co. |
| Nelavu Reed | 208 East 5th St., Lockport, Ill. | 8.50 | Unknown. |
| John Loughridge | Junction Routes 59 and 20, east of Elgin, Ill. | 4.65 | Graduated glass tube. |
| Robert Ward | Duneland Observatory, Ogden Dunes, Ind. | 7.10 | Unknown. |
| Leonard Makila | Addison, Ill. | 5.33 | Do. |
| Mr. Goodwin | About 219th on Maple Ave., west of Park Forest, Ill. | 8.50 | 5-gallon pail with straight sides. |
| Unknown | Tinley Park, Ill., northeast section near 167th St. | 8.40 | Unknown. |
| W. R. Petersen | 5344 Conrad, Skokie, Ill. | 8.36 | Victor rain gage. |
| Bob Smith | 723 South Blvd., Evanston, Ill. | 7.20 | Large container. |
| Frank Wachowski | 2138 West 19th St., Chicago, Ill. | 8.34 | Unknown. |
| McDonald | 8100 South Keating Ave., Chicago, Ill. | 5.75 | 12-inch bucket. |
| Electromotive Division, General Motors | La Grange, Ill. | 6.62 | Unknown. |
| Unknown | Near 109th and Peoria, Chicago, Ill. | 7.40 | Do. |
| Argonne National Laboratory | Lamont, Ill. | 8.64 | Do. |
| Unknown | 1707 South Jefferson St., Chicago, Ill. | 6.50 | 12-inch bucket. |
| Do. | Bensenville, Ill. | 8.00 | 10-gallon bucket. |
| Do. | 3704 West 81st St., Chicago, Ill. | 7.50 | Ice bucket. |
| Do. | 10736 South McVickers, Chicago Ridge, Ill. | 7.25 | Tapered garden cart. |
| W. B. Bailes | 117 West North St., Hinsdale, Ill. | 5.25 | Unknown. |
| Unknown | 3 Luthin Rd., Hinsdale, Ill. | 7.10 | Standard plastic gage. |
| Do. | 806 Dempster, Evanston, Ill. | 6.50 | Gallon bucket. |
| Do. | 5218 North Oak Park Ave., Chicago, Ill. | 7+ | Scrub bucket. |
| Do. | 140th and Central, Midlothian, Ill. | 10.50 | Pail. |
| Do. | Near Montrose and Central Aves., Chicago, Ill. | 8.75 | 30-inch washtub. |
| Mr. Foote | Dolton, Ill. | 10.00 | 18-inch pail with sloping sides. |
| Mr. Aherns | 844 South Garfield Blvd., Chicago, Ill. | [10] 5.34 | Unknown. |
| Unknown | 77th and South Langley, Chicago, Ill. | [11] 2.00 | Clint Youle. |

[1] 1 inch from top of pail.
[2] 2 p. m. Oct. 11–8 a. m. Oct. 12.
[3] Up to 8 a. m. Oct. 11.
[4] Up to about 6 p. m. Oct. 10.
[5] Estimated, 6-inch gage overflowed.
[6] 12½-inch deep tar buckets overflowed.
[7] Oct. 11 and 12.
[8] Estimated.
[9] 24-hour period after beginning of rain.
[10] 9:18 a. m. Oct. 10–7: 10 p. m. Oct. 11.
[11] 2 to 3:20 p. m. Oct. 11.

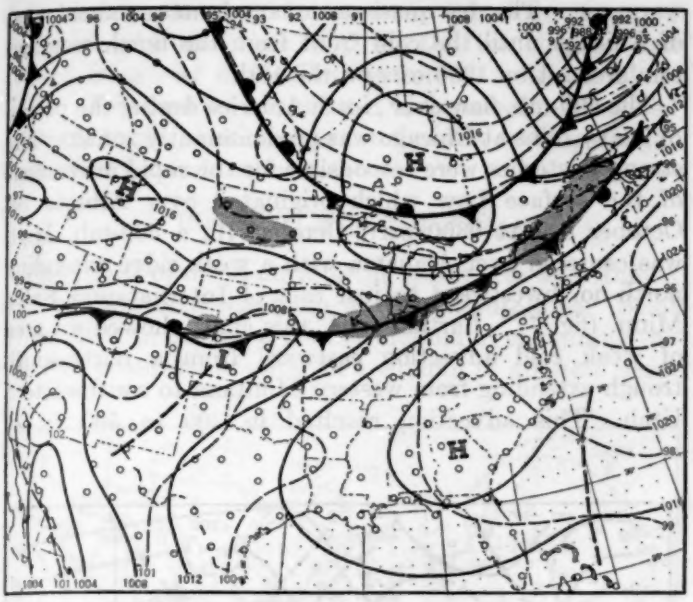

FIGURE 3.—Surface chart at 0330 GMT on October 10, 1954 and 1000 mb. to 700 mb. thickness contours in hundreds of feet (dashed) at 0300 GMT on October 10, 1954. Shading shows areas of active precipitation.

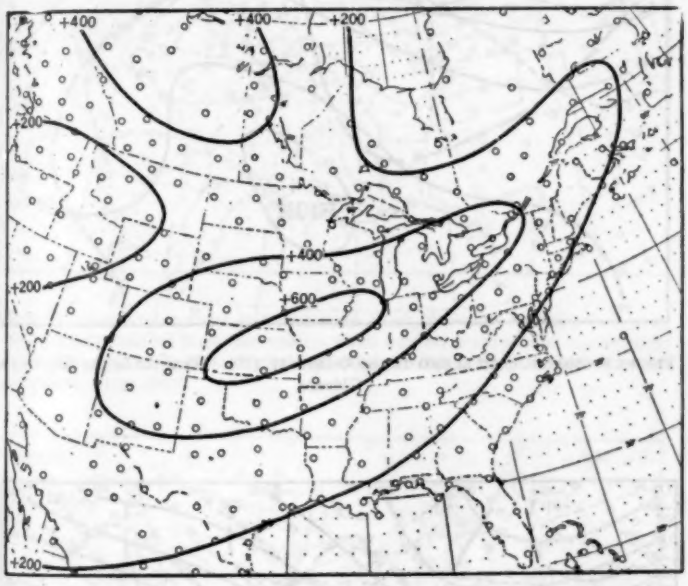

FIGURE 4.—Departure from normal 1000 mb. to 500 mb. thickness at 0300 GMT October 10, 1954, labeled in hundreds of feet. Note that in the area from Chicago southwestward thickness of this layer is 600 ft. or more above normal for October.

moved eastward with a speed of 30 knots. At 0330 GMT, October 10 (fig. 3), it was centered over northern Labrador and had deepened to 987 mb. From this cyclonic circulation, a front extended southwestward to just south of Chicago,[1] then westward to southern Nevada. This map time was about 4½ hours after the Chicago Weather Bureau Office's first report of heavy showers. The dashed lines in figure 3 are thickness lines between 1000 and 700 mb. Since thickness lines are isotherms of mean virtual temperature, the thermal intensity of the front is

[1] Due to the influence of precipitation and thunderstorms on the parameters used to locate fronts, the exact position of that segment of the front through northern Illinois at this time is difficult to determine.

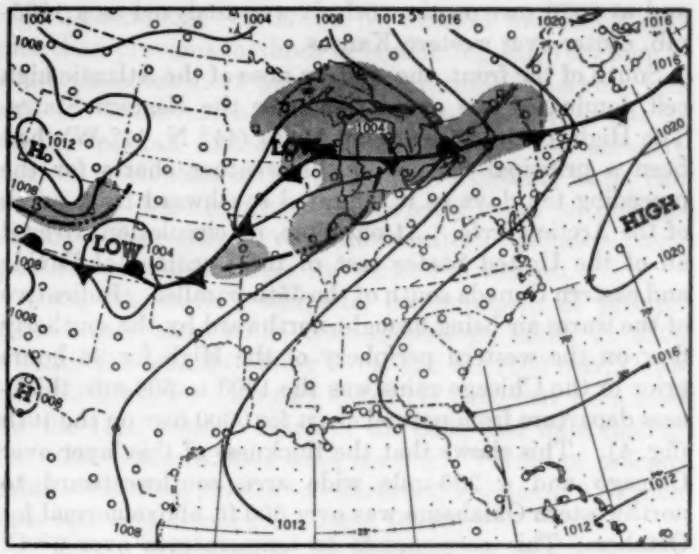

FIGURE 5.—Surface chart at 0330 GMT on October 11, 1954. Note the squall line extending from Michigan through southern Illinois to eastern Kansas.

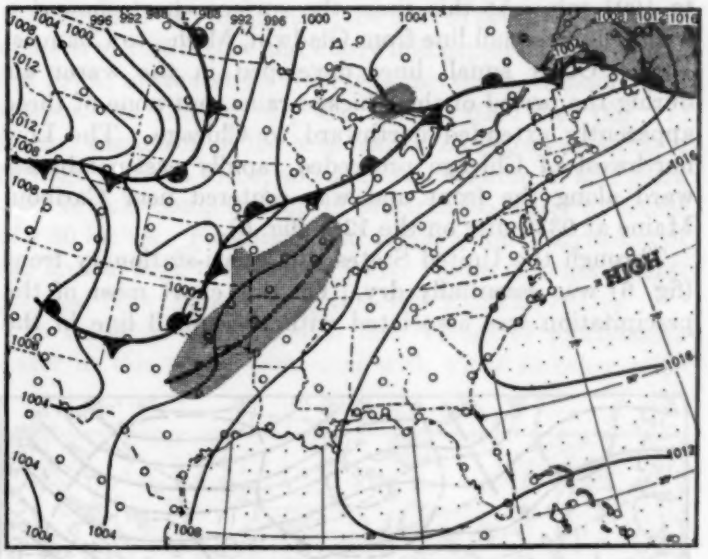

FIGURE 6.—Surface chart at 0330 GMT on October 12, 1954. Chicago is no longer in the precipitation area. The front over the Dakotas passed Chicago by 1230 GMT on October 13, 1954.

clearly shown. Three hours later, the front had moved north of Chicago as a warm front, and throughout the remainder of the precipitation period in the Chicago area, the charts show Chicago in the warm air.

From the same cyclonic circulation in Labrador, a cold front extended through southern Canada, about 200 miles north of the front through the United States, to Fort Smith, District of MacKenzie. By 1530 GMT on the 10th, the eastern portion of this front had replaced the front over the United States, and the western portion had frontolized.

A weak low circulation which first appeared over central South Dakota late on October 8 drifted slowly southward,

and at 0330 GMT on the 10th, it was analyzed as a 1005-mb. center over western Kansas.

South of the front, the western nose of the Atlantic high cell dominated the circulation over the Eastern States. The High, centered near ship Delta (44° N, 41° W), had been a principal feature of the weather charts for the preceding ten days as it migrated southward from north of the Arctic Circle. At one time, its circulation covered all of the United States east of the Continental Divide and eastern Canada south of the 55th parallel. Indicative of the warm air being brought northward by the southerly flow on the western periphery of the High for 36 hours prior to the Chicago rains was the 1000 to 500-mb. thickness departure from normal chart for 0300 GMT on the 10th (fig. 4). This shows that the thickness of this layer over Chicago and a 200-mile wide area southwestward to northwestern Oklahoma was over 600 ft. above normal for October. This corresponds to temperatures over 9° C. above normal.

The weak Low in Kansas on October 10 moved northeastward and at 0330 GMT, October 11 (fig. 5) was centered about 170 miles northwest of Chicago and had deepened to 1001 mb. At this time, the surface chart showed a well defined squall line from Gladwin, Mich., to Chanute, Kans. Other squall lines developed in the warm air during the period of the Chicago rains, but none of these apparently extended northward to Chicago. The Low northwest of Chicago proceeded rapidly east-northeastward along the front and was centered near Caribou, Maine at 0330 GMT on the 12th (fig. 6).

Through the United States, the quasi-stationary front (fig. 6) was essentially dry. On this chart most of the precipitation was associated with the squall line in the warm air. The dry quasi-stationary front remained west of Chicago until the cold front from the northwest had reinforced it by 1230 GMT on the 13th.

The 500-mb. flow over North America during the period of heavy rains at Chicago was predominantly zonal. The strong westerlies were responsible for the rapid movement of the surface Low which originated over Alberta on October 8. At 0300 GMT, October 10, a 500-mb. High was centered over Alabama with a weak ridge extending north-northwestward to just east of International Falls, Minn. (fig. 7). Farther west, this chart showed an area of weak cold advection eastward from a north-south trough extending from western Montana to southwestern Utah. This advection resulted in 300 to 500 ft. of

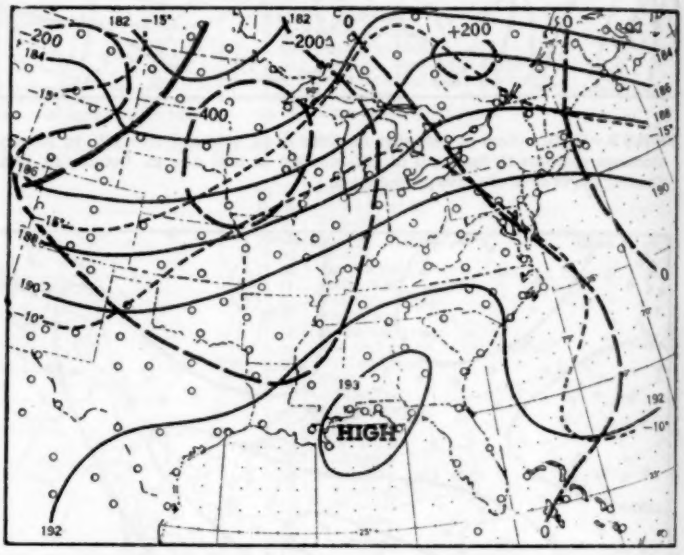


FIGURE 8.—500-mb. chart at 0300 GMT on October 11, 1954. Note the height falls west of Chicago.

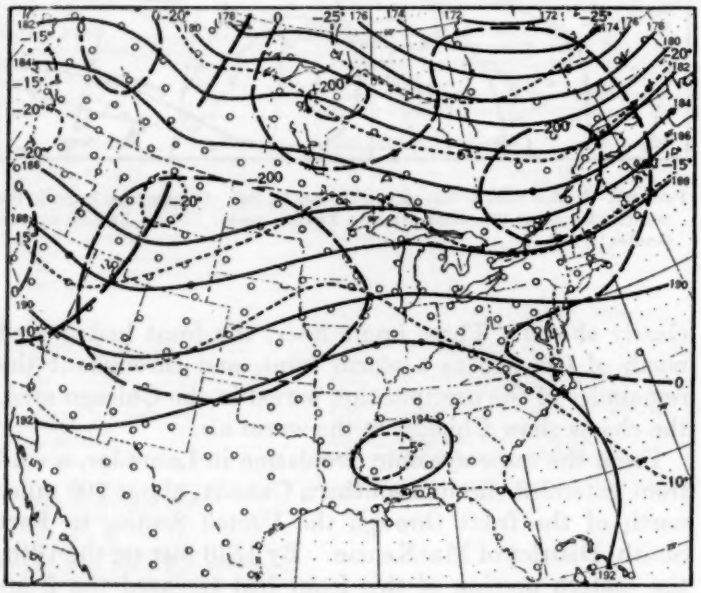

FIGURE 7.—500-mb. chart at 0300 GMT on October 10, 1954. Solid lines are contours in hundreds of geopotential feet. Short dashed lines are isotherms labeled in degrees Celsius. Longer dashed lines denote height changes in feet during the preceding 24 hours. The trough is indicated by a broad dashed line.

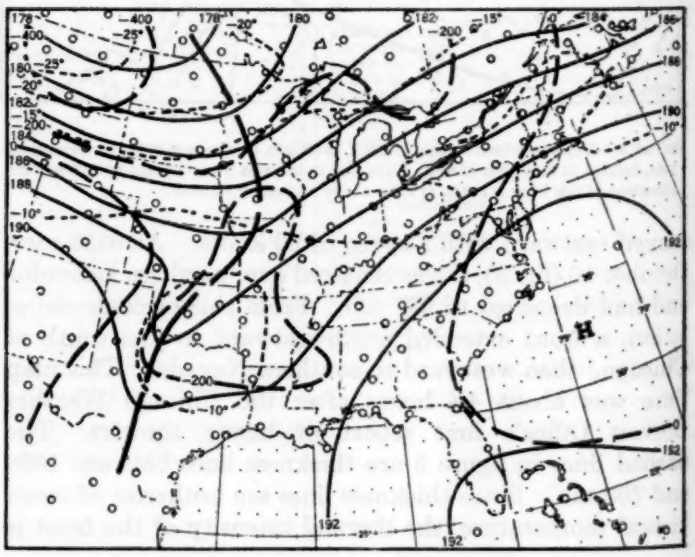


FIGURE 9.—500-mb. chart at 0300 GMT on October 12, 1954.

deepening in the next 24 hours as the ridge migrated eastward. At this time (fig. 8), the trough was well defined from east of Le Pas, Manitoba to southeastern Utah. Twenty-four hours later, this trough had moved eastward to the position shown in figure 9, causing a slight backing of winds to its east.

## INFLOW OF MOIST AIR

The inflow of moist air into the storm area was studied with the aid of precipitable water computations. Solot [2], in 1939, presented a tabular method of computing the value of precipitable water in a column of air from aerological soundings. Although his method was much simpler than previous methods of computing this very significant meteorological parameter, precipitable water was still too inconvenient to compute to have wide use in routine rainfall forecasting. Showalter [3] has recently devised a template with which the precipitable water can be readily obtained from the dewpoint curve on pseudo-adiabatic diagrams. Precipitable water in inches is computed in increments from the surface to 400 mb.

Using Showalter's template, computations of precipitable water were made from soundings taken at 0300 GMT for the period October 8–11, and for 1500 GMT, October 12. Data for 1500 GMT instead of 0300 GMT were used for the 12th because much of the 0300 GMT data desired for other computations were missing. Values of precipitable water were plotted on charts and isolines at 0.50-inch intervals were constructed (figs. 10–14).

Note the high precipitable water values in the vicinity of Topeka, Kans. at 0300 GMT on the 8th (fig. 10), almost two days before the heavy rains began at Chicago. The fact that very moist air moved into the Chicago region is clearly shown by the successive charts. Figure 11 shows that by 0300 GMT on the 9th, the area of precipitable water content of 1.25 inches and above had expanded into southern Iowa, southeastern Nebraska, northern Missouri, and west-central Illinois. By the 10th at 0300 GMT (fig. 12) further expansion of the area had taken place extending it through Indiana, Ohio, and southern Wisconsin, and there were several computations of precipitable water in excess of 1.50 inches. Figures 13 and 14 show the progression of the area of high precipitable water values through Michigan and New York on into the New England States.

In an effort to determine how values of precipitable water in this storm compared with those in other rain-

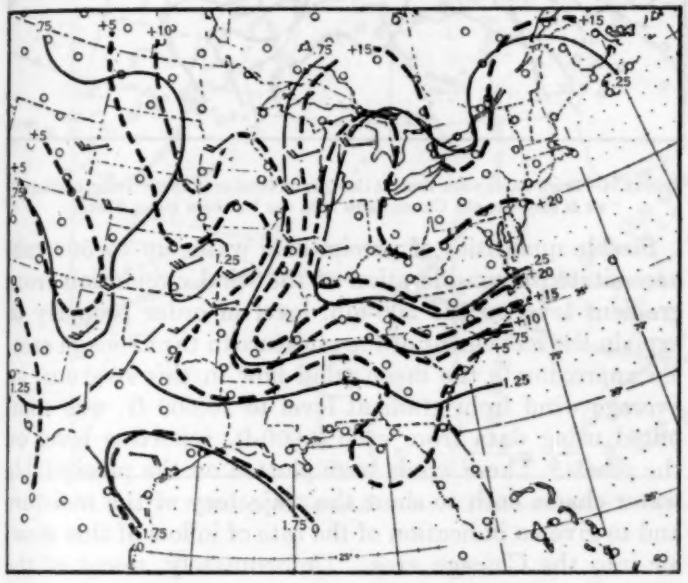

FIGURE 10.—Precipitable water in inches (solid lines), Showalter stability indices in degrees Celsius (dashed lines), and average winds between gradient level and 20,000 ft. at 0300 GMT, October 8, 1954. Henceforth this type chart will be referred to as the precipitable water chart.

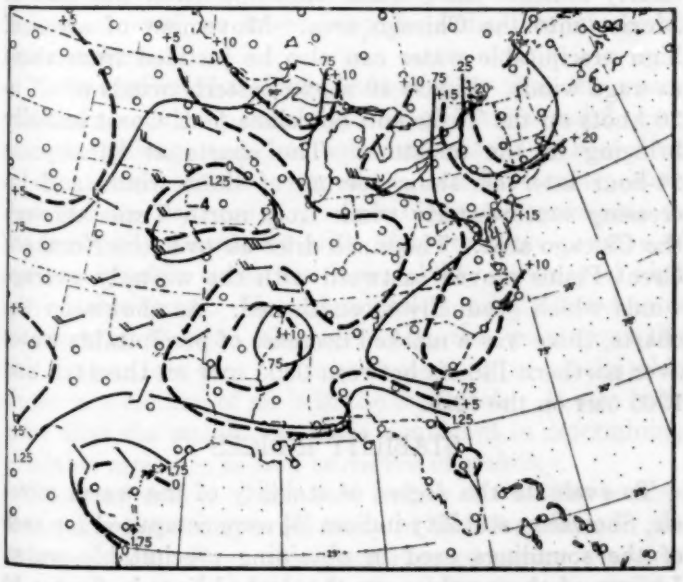

FIGURE 11.—Precipitable water chart at 0300 GMT on October 9, 1954. Note the −4° C. Showalter stability index at Omaha.

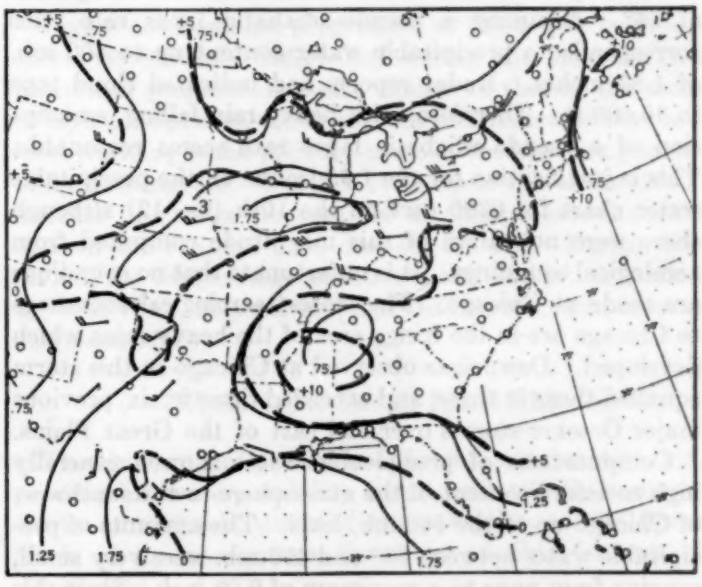

FIGURE 12.—Precipitable water chart at 0300 GMT on October 10, 1954. Precipitable water in the Chicago area has increased markedly and Showalter stability indices are low. Omaha has an index of −3° C.

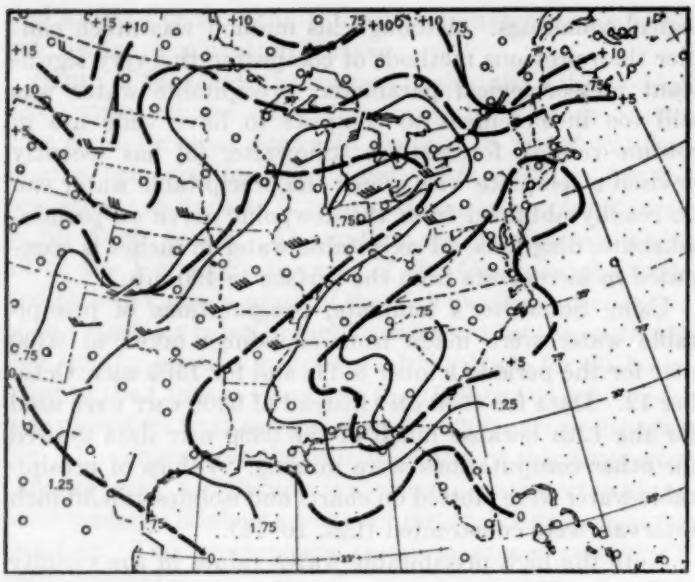

FIGURE 13.—Precipitable water chart at 0300 GMT on October 11, 1954.

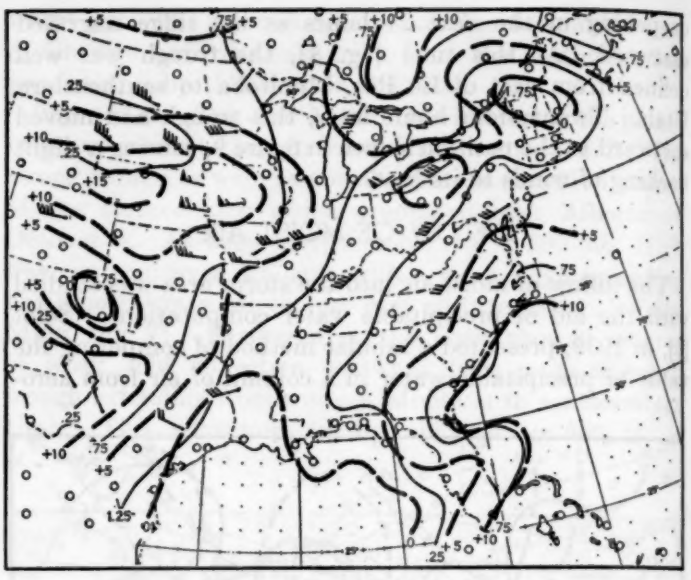

FIGURE 14.—Precipitable water chart at 1500 GMT on October 12, 1954. Drier, more stable air is invading the Chicago area from the Northern Great Plains.

storms, *Hydrometeorological Report* No. 25A [4] was consulted. This report gives the representative dewpoint of each major storm east of the Continental Divide for which dewpoint data had been processed as of June 1949. Included are storms since 1867. From this list, dewpoints of all storms occurring in October north of 35° latitude were tabulated. Sixteen storms fell into this category. Dewpoint values ranged from a low of 60° to a high of 74° F. The average was found to be 66°. It is worthy of mention that none of these October storms occurred west of the Great Plains.

The average dewpoint found in past October storms compares favorably with observed values in the Chicago rainstorm. During their initial thundershower period the Chicago Weather Bureau Office reported dewpoints. of 66°. Assuming a pseudo-adiabatic lapse rate, this corresponds to precipitable water content up to 400 mb. of 1.83 inches. Radar reports had indicated cloud tops to 40,000 ft. Therefore, with heavy rain falling, assumption of a pseudo-adiabatic lapse rate seems reasonable. This is justification for the 1.75 isoline on the precipitable water chart for 0300 GMT on the 10th (fig. 12) although there were no values of this magnitude computed from aerological soundings. It is unfortunate that no soundings are made at Chicago. The closest aerological soundings to Chicago are in the fringe area of the heavy rains which developed. Dewpoints observed at Chicago in this storm equalled those in three, and exceeded those in six, previous major October storms over and east of the Great Plains.

Computations of precipitable water showed generally high moisture content of the atmosphere to the southwest of Chicago up to the 500-mb. level. The amounts of precipitable water between 500 and 400 mb. were very small, ranging from none to a maximum of 0.09 inch. Since this quantity is only a small percentage of the total precipitable water, it may be neglected.

Sizable quantities of precipitable water up to 500 mb. necessitated a consideration of the wind circulation from gradient level to the 500-mb. level in order properly to explain the movement of the moisture in the Chicago area. To approximate the mean wind flow in this stratum, an average wind from gradient level to 20,000 ft. was computed using data from each 2,000-ft. reporting level on the pibals. These winds were plotted on the precipitable water charts both to show the trajectory of the moisture and to give an indication of the rate of inflow of this moist air into the Chicago area. Unfortunately, many of the wind observations ended below 20,000 ft. and the number of average winds for the stratum from gradient level to 20,000 ft. was too limited to pinpoint an axis of strongest average wind. However, enough data were obtained to clearly indicate the general wind flow from the Gulf of Mexico into the Chicago area. Movement of areas of high precipitable water can also be justified from these average winds. Figure 10 shows easterly winds of 15 to 20 knots on the Texas and Louisiana Gulf Coast initially bringing in the moisture. The charts at subsequent 24-hour intervals show veering of these winds and increasing southwesterly winds from north Texas through the Chicago area. The much drier air over the Northern Great Plains moved eastward with the westerly average winds which gradually strengthened. As shown on the charts, there was a marked decrease of precipitable water over northern Illinois between 0300 GMT on the 11th and 1500 GMT on the 12th.

## STABILITY INDICES

To evaluate the degree of stability of the warm moist air, Showalter stability indices [5] were computed for each of the soundings used in obtaining precipitable water. Isolines of these values are the dashed lines in figures 10 through 14. Negative values indicate instability and posi-

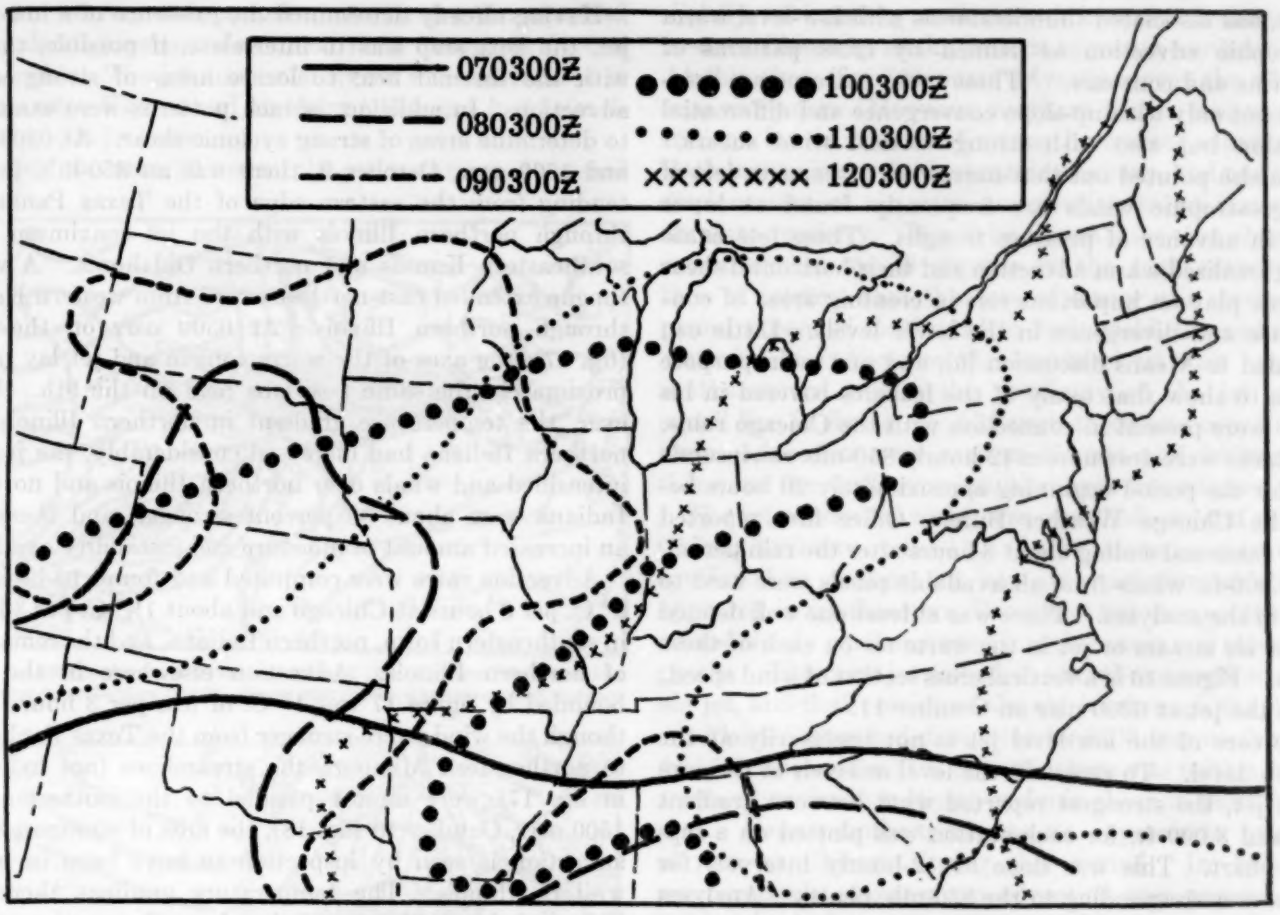


FIGURE 15.—Progression of the 10° C. isodrosotherm at the 850-mb. level from 0300 GMT on October 7 to 0300 GMT on October 12, 1954.

tive values, stability. As mentioned by Showalter [5], experience has shown that any positive value of +3° or less is very likely to be associated with showers and quite likely to produce thunderstorms. Thunderstorms have increasing probability as the index falls from +1° to −2°. Values of −3° or lower may be indicative of severe thunderstorms.

The patterns of stability indices show that the warm moist air coming up from the Gulf of Mexico and flowing into the Chicago area had sufficient instability according to the above criteria to produce thunderstorms. Note how well the patterns of precipitable water correspond to the patterns of stability with high stability in areas of low precipitable water and low stability in areas of high precipitable water. Since the stability index is based upon moisture at the 850-mb. level only, this points out the well known fact that the largest quantity of precipitable water in a column of air is in the low levels. It also indicates that the stability index is significant in determining available moisture as well as degree of stability.

The progression of the zero isoline of stability indices shows the increasing probability of thunderstorms in the Chicago area. Even the possibility of severe thunderstorms was indicated by the −4° stability index at Omaha on the 9th at 0300 GMT. Omaha was directly upstream from Chicago. On the 10th at 0300 GMT Omaha had an index of −3° and the unstable air was again pouring directly into the Chicago area as shown by the average winds.

Figure 15 shows the progression of the 10° C. isodrosotherm at 850 mb. before and during the storm. This pattern of progression is also similar to that of the areas of high precipitable water content and indicates that low level warming is the primary cause of the increasing instability downstream. Further evidence of this is the 12° C. increase in surface temperature at Omaha between 0300 GMT on the 8th and 0300 GMT on the 9th. During this period, the temperature at 850 mb. and 700 mb. increased 11° and 4° C., respectively, and the 500-mb. temperature decreased 2° C.

## OTHER LOW-LEVEL FEATURES

The similarity of patterns of the three parameters, viz, precipitable water, stability index, and 10° C. isodrosotherm at 850 mb. directed our attention to the lower levels of the atmosphere for other possible features of significance.

Means [6], in a comprehensive study of the occurrence and forecasting of thunderstorms in the central United

States, has associated thunderstorms with low-level warm geostrophic advection as defined by cross patterns of isotherms and contours. "These cross patterns are associated not only with up-slope convergence and differential advection but also with strong vertical wind shears." Means also pointed out that narrow air streams or jets of supergeostrophic winds are frequently found at lower levels in advance of pressure troughs. These jets cause strong localized warm advection and their horizontal shear patterns play an important role in creating areas of convergence and divergence in the lower levels. Little can be added to Means discussion [6], and our main purpose here is to show that many of the features covered in his article were present in connection with the Chicago rains.

Isotachs were drawn from 12-hourly 850-mb. rawinsonde data for the period beginning approximately 20 hours before the Chicago Weather Bureau Office first reported heavy rains and ending about 8 hours after the rain period. The 5,000-ft. winds from all available pibals were used to assist in the analyses. There was at least one well defined narrow air stream or jet in the warm air on each of these charts. Figure 16 is a vertical cross section of wind speeds across the jet at 0300 GMT on October 11.

The core of the low-level jet is not necessarily at the 850-mb. level. To ascertain the level or levels of the core of the jet, the strongest reported wind between gradient level and 8,000 ft. for each station was plotted on a separate chart. This was done at 12-hourly intervals for the times corresponding to the 850-mb. charts. Analyses of these data showed that for the most part the strongest wind was at the 5,000-ft. level (approximately 850-mb. level). In cases where the strongest wind was at another level, it usually was not much stronger than the wind at 5,000 ft. The axes of strongest winds on the two charts for a given time did not differ significantly.

Because the 850-mb. charts were found to be satisfactory to demonstrate the low-level jet and because temperature patterns could readily be obtained from these charts, use of this level was made in this phase of our study.

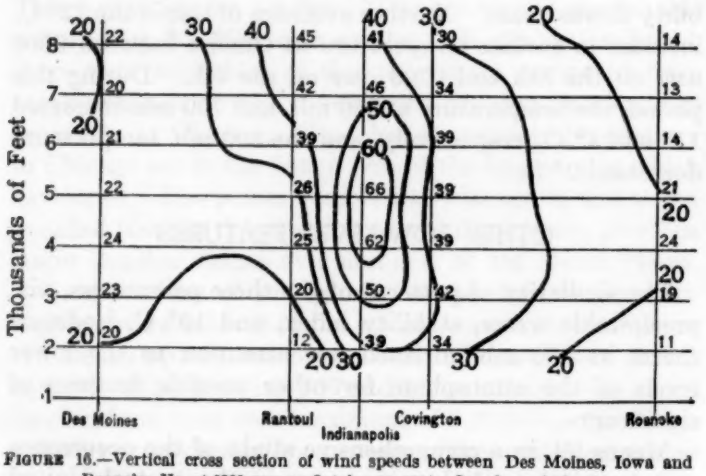


FIGURE 16.—Vertical cross section of wind speeds between Des Moines, Iowa and Roanoke, Va. at 0300 GMT on October 11, 1954. Speeds are in knots.

Having already determined the existence of a low-level jet, the next step was to interrelate, if possible, the jet with the thermal field to locate areas of strong warm advection. In addition, isotach patterns were examined to determine areas of strong cyclonic shear. At 0300 GMT and 1500 GMT, October 9, there was an 850-mb. jet extending from the eastern edge of the Texas Panhandle through northern Illinois with the jet maximum over southeastern Kansas and northern Oklahoma. A warm tongue extended east-northeastward from western Kansas through northern Illinois. At 0300 GMT on the 10th (fig. 17), the axes of the warm tongue and jet lay in approximately the same positions held on the 9th. However, the temperature gradient in northern Illinois and northern Indiana had increased considerably, the jet had intensified and winds over northern Illinois and northern Indiana were about 30 percent stronger, and there was an increased amount of moisture and instability available.

Advection rates were computed and found to be about 2° C. per 3 hours at Chicago and about 1½° C. per 3 hours in southeastern Iowa, northern Indiana, and the remainder of northern Illinois. Advection elsewhere in the area bounded by figure 17 was 1° C. or less per 3 hours. Although the winds were stronger from the Texas Panhandle to northeastern Missouri, the streamlines (not indicated in fig. 17) were almost parallel to the isotherms. At 1500 GMT, October 10 (fig. 18), the area of strongest warm advection is seen by inspection to have been in northwestern Illinois. The temperature gradient there had increased due both to warming from the southwest and to precipitational cooling over north-central Illinois and northern Indiana. At 850 mb., Rantoul, Ill., had cooled 3° C. while Columbia, Mo. had warmed 2° C. Moline, Ill., accumulated twice as much rain (3.65 inches) in the 12 hours between 0630 and 1830 GMT as Chicago (1.83

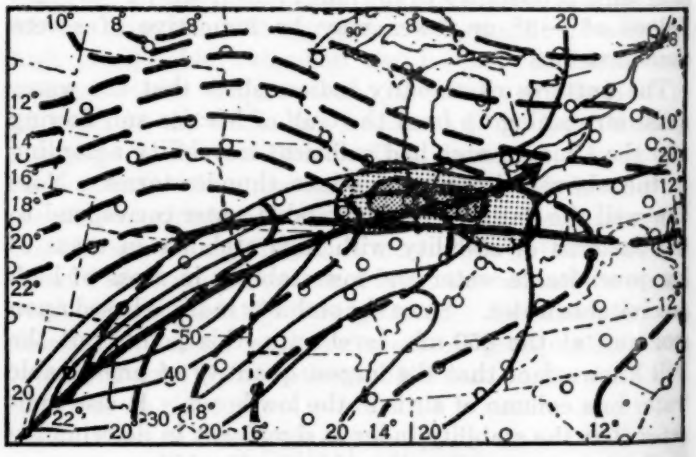

FIGURE 17.—850-mb. chart at 0300 GMT on October 10, 1954. Heavy solid line is axis of jet. Heavy dashed line is axis of warm tongue. Light solid lines are isotachs labeled in knots. Light dashed lines are isotherms labeled in degrees Celsius. Light shading denotes rainfall of over 0.25 inches in period beginning 8¾ hours before and ending 3¼ hours after chart time for first-order stations in United States. Heavy shading indicates rainfall of over an inch in the same period. Note that the axis of the jet and the axis of the warm tongue cross in northern Illinois.

inches). During the preceding 12 hours, Chicago had accumulated nine times as much (2.33 inches) as Moline (0.26 inch). The jet maximum which was still located in southeastern Kansas and northern Oklahoma had intensified to about 70 knots.

During the next 12 hours, the jet maximum decreased slightly in intensity and moved into the Indiana and western Ohio area as the jet axis migrated southeastward. At this time (fig. 19) warm advection over the Chicago area was weak. However, northern Illinois and northern Indiana lay in a zone of strong horizontal convergence. Both increasing cyclonic shear downstream and northward displacement of air were contributing to an increase in absolute vorticity. It will be shown later that there was concurrent strong divergence in the high troposphere. It is of interest that the area of heavy rain during this period expanded southward to Springfield, Ill., and southeastward in Indiana as the low level jet axis migrated southeastward. Note the proximity of the jet to the squall line in figure 5. Although there was considerable warm advection over eastern Kansas and Missouri at this time, the air flowing into that area was relatively dry.

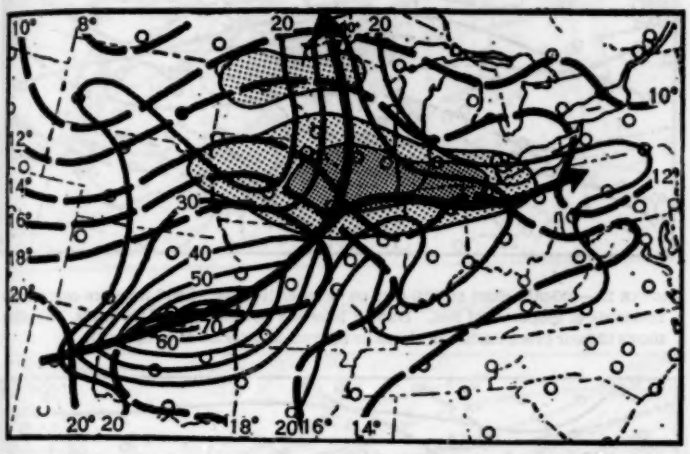

FIGURE 18.—850-mb. chart at 1500 GMT on October 10, 1954. Strongest warm advection has shifted to northwestern Illinois. Heavy precipitation area has expanded westward.

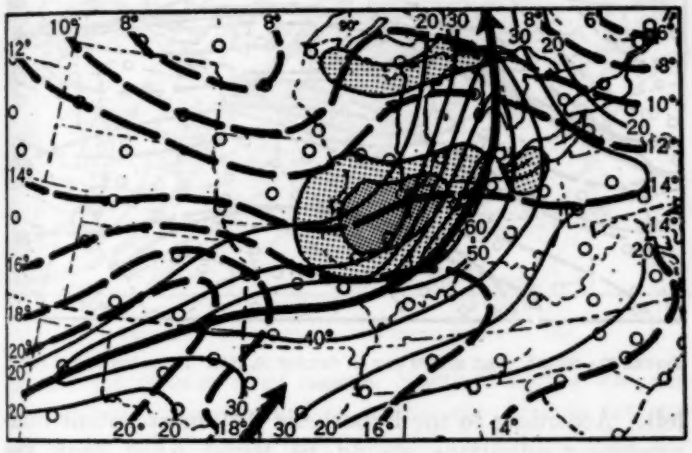

FIGURE 19.—850-mb. chart at 0300 GMT on October 11, 1954. Jet maximum has moved northeastward and jet axis has migrated southeastward.

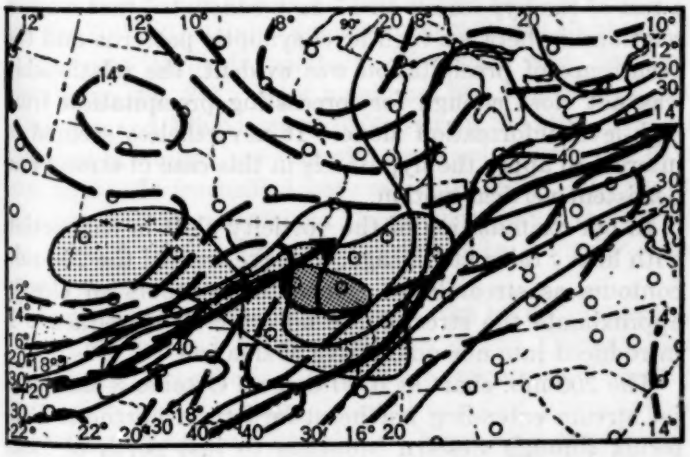

FIGURE 20.—850-mb. chart at 1500 GMT on October 11, 1954. Southern portion of old jet has fractured and a new jet maximum has intensified and moved slowly into Arkansas.

The jet maximum which was over Indiana and western Ohio at 0300 GMT on the 11th (fig. 19) moved eastward and continued to weaken. A new jet maximum which first appeared in northeastern Texas at 1500 GMT on the 10th moved slowly northeastward into Arkansas and intensified slowly. This new jet joined the northern portion of the old jet, and that portion of the old jet through the Southern Plains States had dissipated by 0300 GMT on the 12th. At 1500 GMT on the 11th (fig. 20), there was neither strong warm advection nor strong cyclonic shear in the Chicago area. Consequently there was no appreciable quantity of rain at Chicago during this period. In Missouri, comparatively strong warm advection was present. Air flowing into that area was somewhat more moist than 12 hours earlier and rainfall increased sharply during this period.

On the afternoon of October 11, about 4½ hours after the chart time in figure 20, a brief period of heavy showers resulted in as much as 2 inches of rain in 2 hours on Chicago's South Side. The Chicago Weather Bureau Office accumulated 0.48 inch. The reasons for rain of this intensity during that period cannot be explained by the 850-mb. data either for 1500 GMT on the 11th or for 0300 GMT on the 12th. In addition, there were insufficient upper air data for 2100 GMT on the 11th to explain this occurrence. However, one factor of possible significance is the 4° C. increase in temperature at 850 mb. at Columbia, Mo., between 1500 and 2100 GMT on the 11th while the temperature at Rantoul remained unchanged. This suggests that the temperature gradient and consequently the advective rate had increased in the Chicago area. Available wind data for 2100 GMT indicate that the low-level jet lay through southern Illinois and central Indiana but no strong cyclonic shear was indicated in the Chicago area. Surface analyses show that the front remained northwest of Chicago during this period.

## THE JET STREAM AND VORTICITY IN THE HIGH TROPOSPHERE

Most studies of the high-level jet stream in its relation to precipitation have been made at the 300-mb. level.

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This level has been so frequently used because, of those mandatory levels reported in radiosonde observations, it normally is the one on which the jet stream is best defined. However, during the period under discussion, the tropopause was above the 200-mb. level and the core of the jet stream was closer to the 200-mb. level than to the 300-mb. level. Since the jet stream was better defined at 200 mb., this level was chosen for our study.

Starrett [7], in his examination of 57 synoptic situations showed that maxima of precipitation usually occur under the jet stream at 300 mb. with a standard deviation of maxima of approximately 5° of latitude. Since even in the locations most favorable for precipitation, 19 percent of Starrett's cases reported no precipitation, one of his conclusions was that the dynamics of the jet stream produce only a broadscale effect on the dynamical fields of convergence and divergence associated with the short baroclinic waves within the westerlies. The good correlation between the high tropospheric jet stream and precipitation found by Starrett was indicative of a tendency for upward motions to be accentuated underneath the jet stream. A more recent investigation by Endlich [8] has shown that strong isanabatic [2] centers lie in or near the jet stream indicating that it is an important vertical transport mechanism. Norquest [9] noted that nearly all precipitation areas of large size over the United States are connected with the jet stream and that even the majority of smaller patchy areas (up to the size of a State) are related to the high-level flow. Other studies have related vertical motion to the vorticity field of the atmosphere. Petterssen [10] showed that "deep" and "very deep" convection are almost exclusively associated with cyclonic vorticity aloft. His results were based on about 300 soundings. The convection was classified as "shallow," "deep," or "very deep" according as the tops of the convective clouds were below the 800-mb. level, between the 600- and 400-mb. levels, or above the 400-mb. level, respectively. Following articles by Sutcliffe [11], Sawyer [12], and Palmén [13] on the relations between the vorticity field of the atmosphere and large-scale vertical motion, Riehl, Norquest, and Sugg [14] developed an equation relating vertical motion in the lower troposphere to the vertical component of the vorticity field of the upper troposphere which associated upward motion with decreasing relative vorticity downstream and downward motion with increasing relative vorticity downstream along streamlines.

The vertical component of relative vorticity is defined by:

$$\zeta = kV - \frac{\partial V}{\partial n}$$

where $k$ is the streamline curvature positive for cyclonic curvature, $V$, the wind speed, and $n$ is distance along an axis perpendicular to the streamline and positive to the left. According to the hypothesis [14], most potent rain-producing situations should be found when both the curvature and the wind shear are decreasingly cyclonic downstream along the streamlines. Teweles [15] after a test of the hypothesis on 17 days concluded that while a relationship between high level synoptic patterns and the occurrence of precipitation was evident, the relationship was not close enough for forecasting precipitation from high-level information alone. It nevertheless seemed of interest to apply the hypothesis in this case of strong and persistent vertical motion.

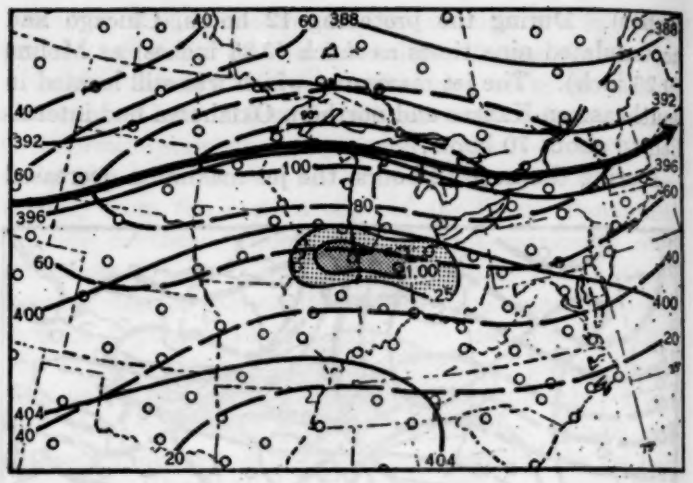


FIGURE 21.—200-mb. chart at 0300 GMT on October 10, 1954. Solid lines are contours in hundreds of geopotential feet. Dashed lines are isotachs labeled in knots. Shading shows 12-hour precipitation for the same interval and period as in figure 17.

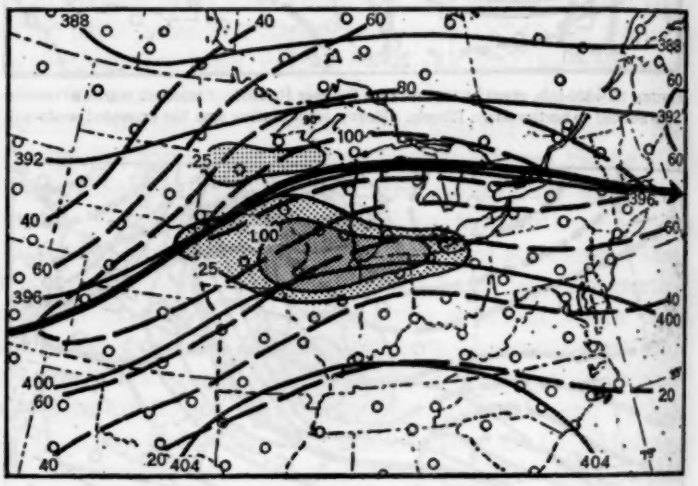


FIGURE 22.—200-mb. chart at 1500 GMT on October 10, 1954. Ridge has moved east of Chicago.

In our examination of the vorticity aloft in connection with heavy rains at Chicago, we have treated the 200-mb. contours as streamlines. Since the contours so closely approximate the streamlines, no error of consequence is introduced into our qualitative evaluation.

The 200-mb. chart at 0300 GMT on October 8 showed a jet stream extending northeastward from northern California through western Montana to just north of Lake Winnepeg then southeastward through the southern New England States. During the next 12 hours, the portion

[2] An isanabat is a line of constant vertical velocity.

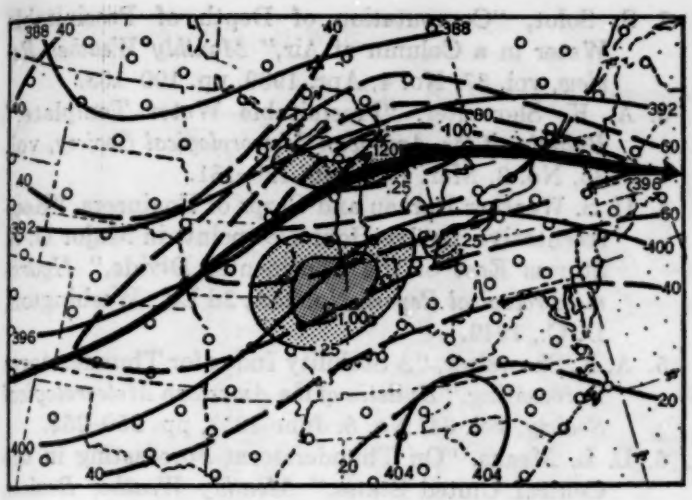


FIGURE 23.—200-mb. chart at 0300 GMT on October 11, 1954.

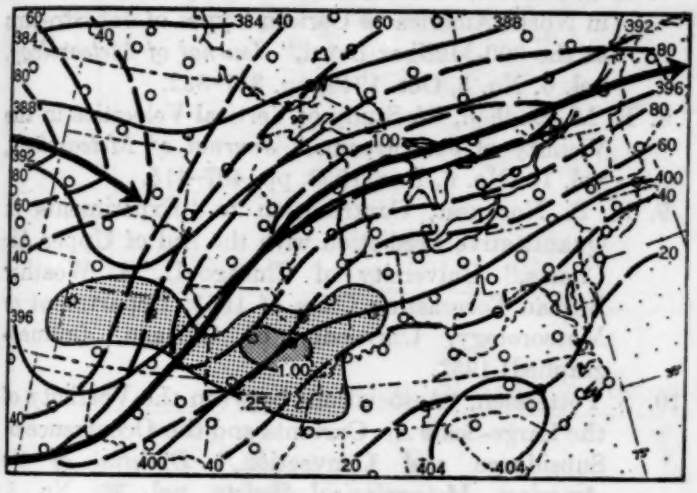


FIGURE 24.—200-mb. chart at 1500 GMT on October 11, 1954.

of the jet stream over central North America was displaced rapidly southward as a Low moved into extreme north-central Canada from the Arctic Ocean. At this time, the jet stream was near the northern border of the United States. During the 9th, the jet stream was displaced southward at a much slower rate and, at 0300 GMT on the 10th, it extended across southern South Dakota and Minnesota through northern Wisconsin and northern Michigan (fig. 21). A jet maximum was located over the Dakotas and Minnesota at 0300 GMT on the 9th. This jet maximum moved very slowly eastward during the next 2½ days. It intensified between 0300 and 1500 GMT on the 9th and then remained strong throughout the period of rainfall with only minor variation in intensity from chart to chart.

During most of the rainy period, the jet maximum was favorably located for precipitation in the Chicago area under the hypothesis [14] being considered. The only exception was the time of initial onset of precipitation. At 0300 GMT on the 10th, about 4 hours after the Chicago Weather Bureau Office first reported heavy rain, the ridge line was a short distance west of Chicago and the maximum wind was on the ridge. Chicago was in a position where at the 200-mb. level there was a slight decrease in both anticyclonic shear and curvature downstream along the streamlines. Both of these conditions contribute to increasing relative vorticity downstream. The same conditions were existent at 300 mb. It appears therefore, that the gradient of relative vorticity in the high troposphere did not initially account for the rain occurrence according to the hypothesis. Further testimony to this was the heavy rain which fell over northern Indiana and over sections of northwestern Ohio where there can be little doubt that the relative vorticity was increasing downstream. Note that during the next 36 hours (figs. 22–24), the 200-mb. ridge moved slowly eastward. On each of the 12-hour charts, heaviest rainfall during the period beginning 8½ hours before and ending 3½ hours after chart time was in an area where at 200 mb. an increase in anticyclonic shear and an increase in anticyclonic curvature downstream were both contributing to decreasing relative vorticity downstream. The vertical motions resulting from the strong divergence aloft inferred from this vorticity field in the high troposphere, in conjunction with favorable conditions in the low levels, contributed to the prolongation of rainfall in the Chicago area. It is reasonable to assume that this condition was also a factor of importance in the intensity of the rainfall.

At 0300 GMT on October 12, 4½ hours after the Chicago Weather Bureau Office's last report of showers on the hourly sequences, the 200-mb. chart indicated that the jet axis had been displaced rapidly southeastward to a position south of the Chicago area. Chicago was no longer in a position relative to the jet maximum to have divergence in the high troposphere since it was in a sector where the relative vorticity was increasing downstream.

## SUMMARY

It has been shown that the air flowing into the Chicago area throughout the rain period was warm and very moist. This air had potential instability exceeding that necessary to produce thunderstorms. An increase in average winds between gradient level and 20,000 ft. increased the rate of inflow of moist air into the area. At the initial onset of heavy precipitation, an increase in low level warm advection had developed as a result of strengthening of an 850-mb. jet which extended northeastward from the eastern border of the Texas Panhandle. The 850-mb. warm tongue, which extended east-northeastward from western Kansas, crossed the 850-mb. jet in northern Illinois. This increase in low level warm advection implies increased upslope convergence Frontal convergence apparently was also a part of the initial rain-producing mechanism. The surface chart 7½ hours after heavy rain was first reported by the Chicago Weather Bureau Office showed that the front had moved north of Chicago. Chicago was in the warm air sector during the remainder of the 48-hour period of rains. At 1500 GMT on the 10th, the low level

warm advection was still present, but much stronger over northwestern Illinois than in the Chicago area. Consequently the heaviest rain area shifted to northwestern Illinois. The 850-mb. temperature gradient there had increased due to both warming from the southwest and precipitational cooling over northern and central Illinois and northern Indiana.

In the meantime, the 200-mb. ridge moved slowly eastward and the vorticity field associated with the high tropospheric jet maximum had created a zone of strong divergence aloft over the area of concern. At 0300 GMT on the 11th, warm advection in the Chicago area was weak. However, northeastward movement of the low level jet maximum together with southeastward migration of the jet axis had created strong horizontal convergence in the low levels over northern Indiana and over most of Illinois. In the high troposphere, the divergence inferred from decreasing relative vorticity downstream, was persistently strong. At 1500 GMT on the 11th, there was neither strong warm advection nor strong horizontal convergence over the Chicago area in the low levels. Rainfall decreased sharply during this period. Divergence continued in the high troposphere.

The brief period of heavy showers at Chicago during the afternoon of the 11th is not fully explained. However, sparse data at 850 mb. near the time of occurrence suggest that the advective rate of warm air had increased. Divergence in the high troposphere was still present. The last time the Chicago Weather Bureau Office reported showers on hourly sequence reports was at 2230 GMT on the 11th. Rawinsonde data 4½ hours later indicated that much drier air was flowing into the Chicago area from the Great Plains States except in a shallow layer near the ground. The 200-mb. jet axis had been displaced rapidly southeastward and Chicago was no longer in a position relative to the jet maximum to have divergence in the high troposphere.

## ACKNOWLEDGMENTS

The writers wish to express their appreciation to the Chicago Weather Bureau Office for furnishing helpful ideas and material; to A. K. Showalter and F. W. Burnett for many helpful suggestions and for reviewing the article; to the Daily Map Unit of the Weather Bureau for detailed drafting of figures; and to J. J. Smiles for his tireless efforts in computing parameters and preparing charts for analysis.

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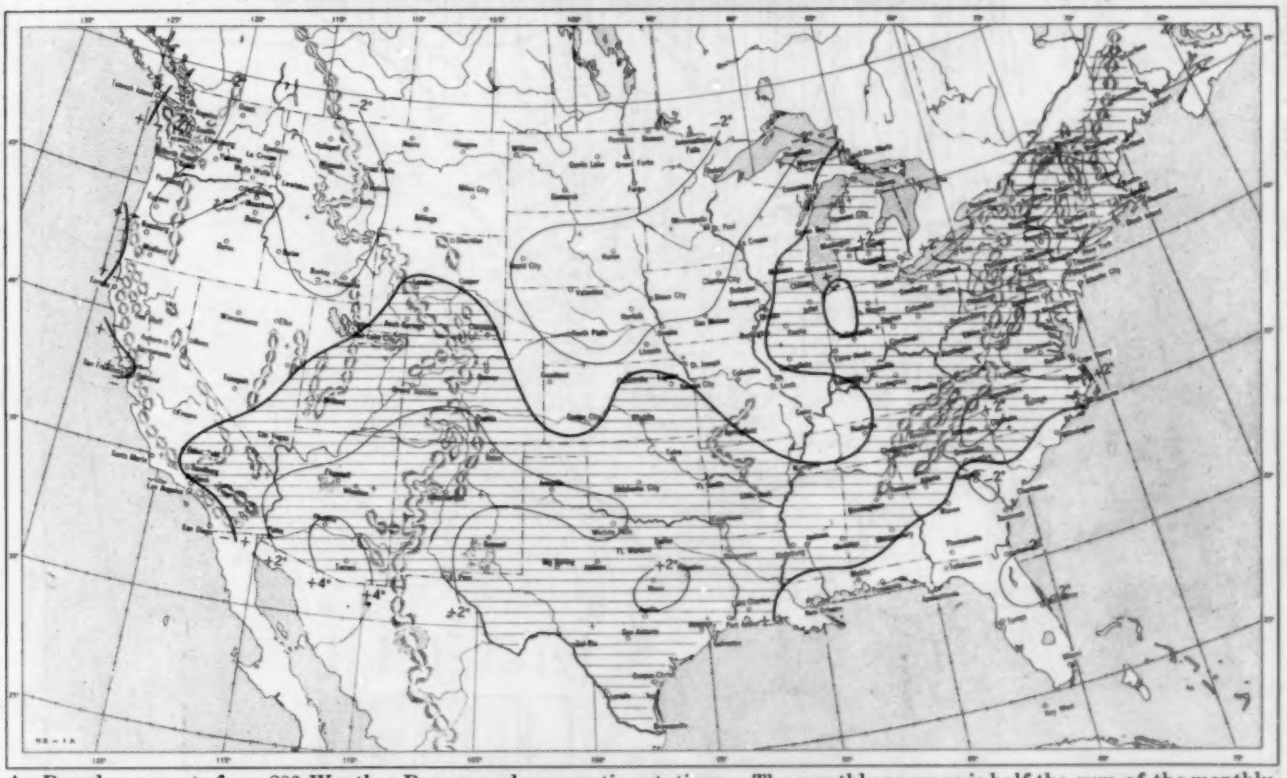
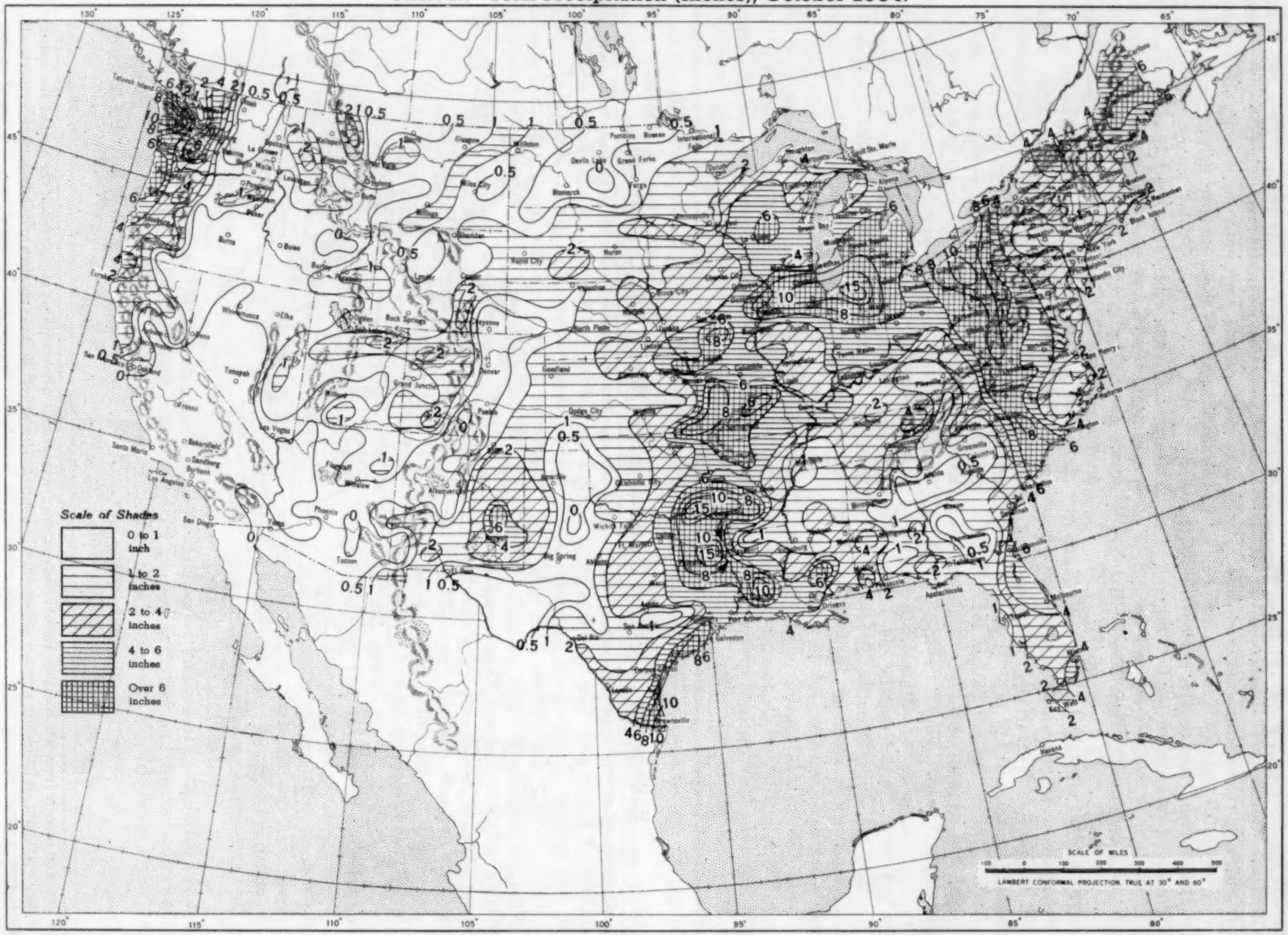
## Chart I. A. Average Temperature (°F.) at Surface, October 1954.

## B. Departure of Average Temperature from Normal (°F.), October 1954.



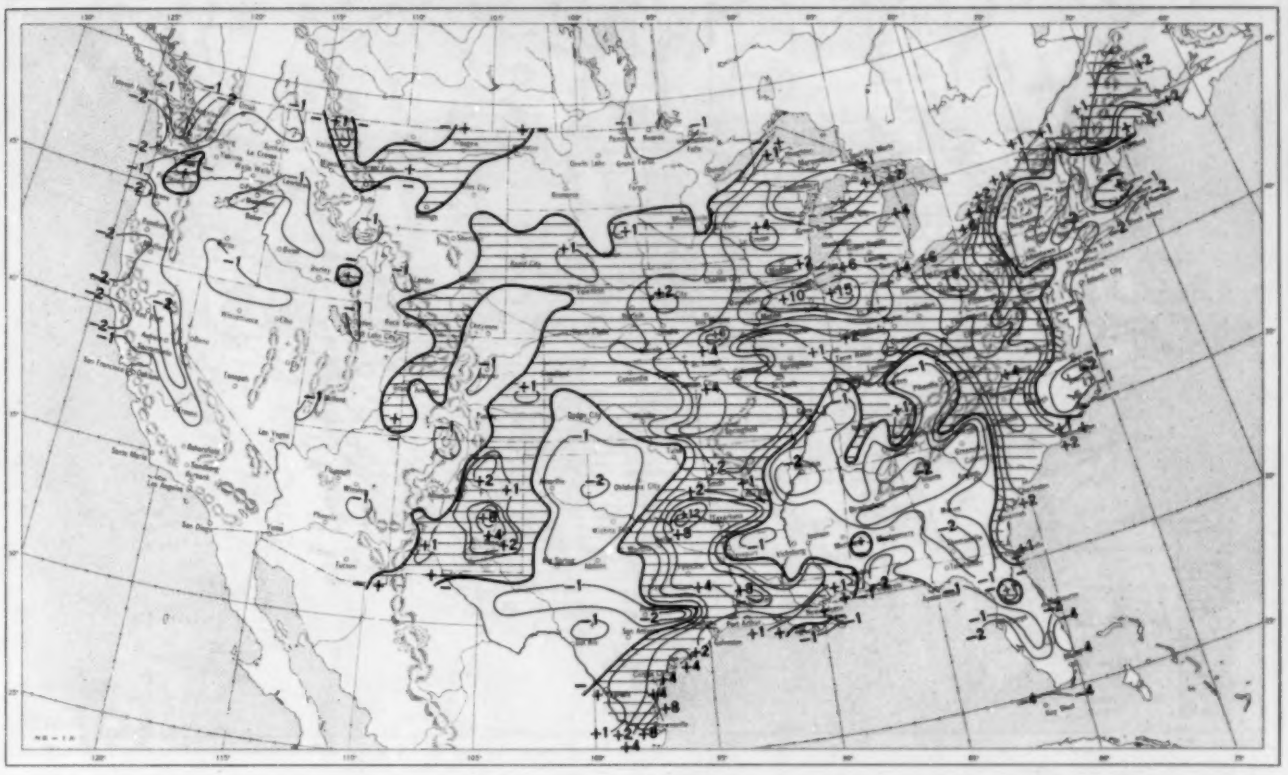
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

## Chart II. Total Precipitation (Inches), October 1954.

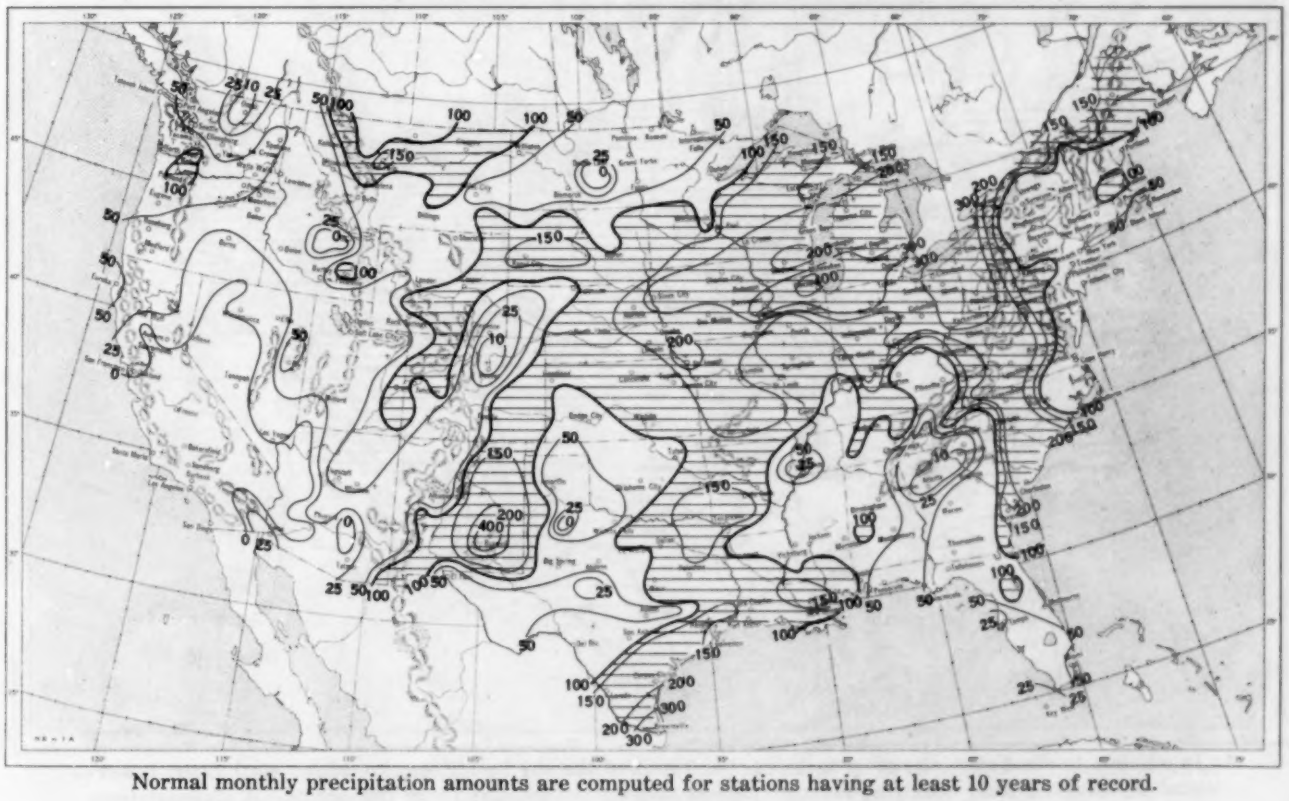

Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 60°

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

## Chart III. A. Departure of Precipitation from Normal (Inches), October 1954.

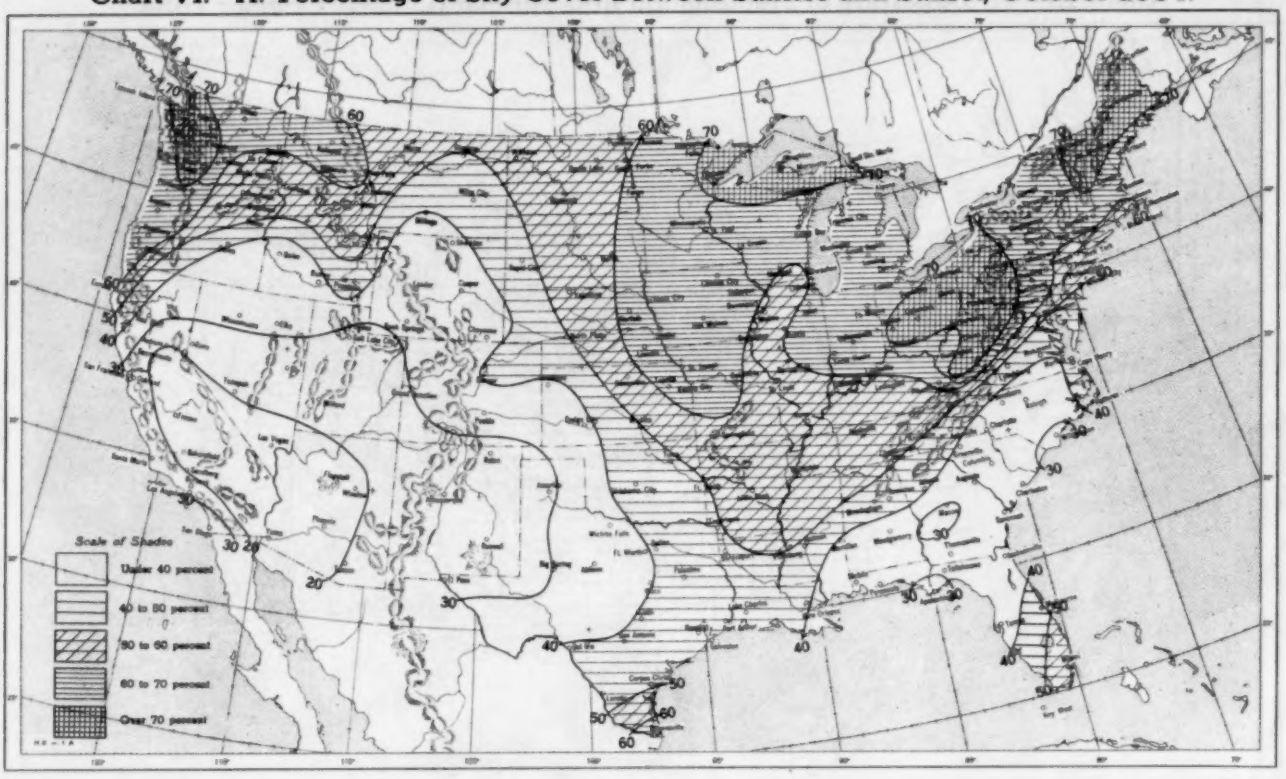


## B. Percentage of Normal Precipitation, October 1954.

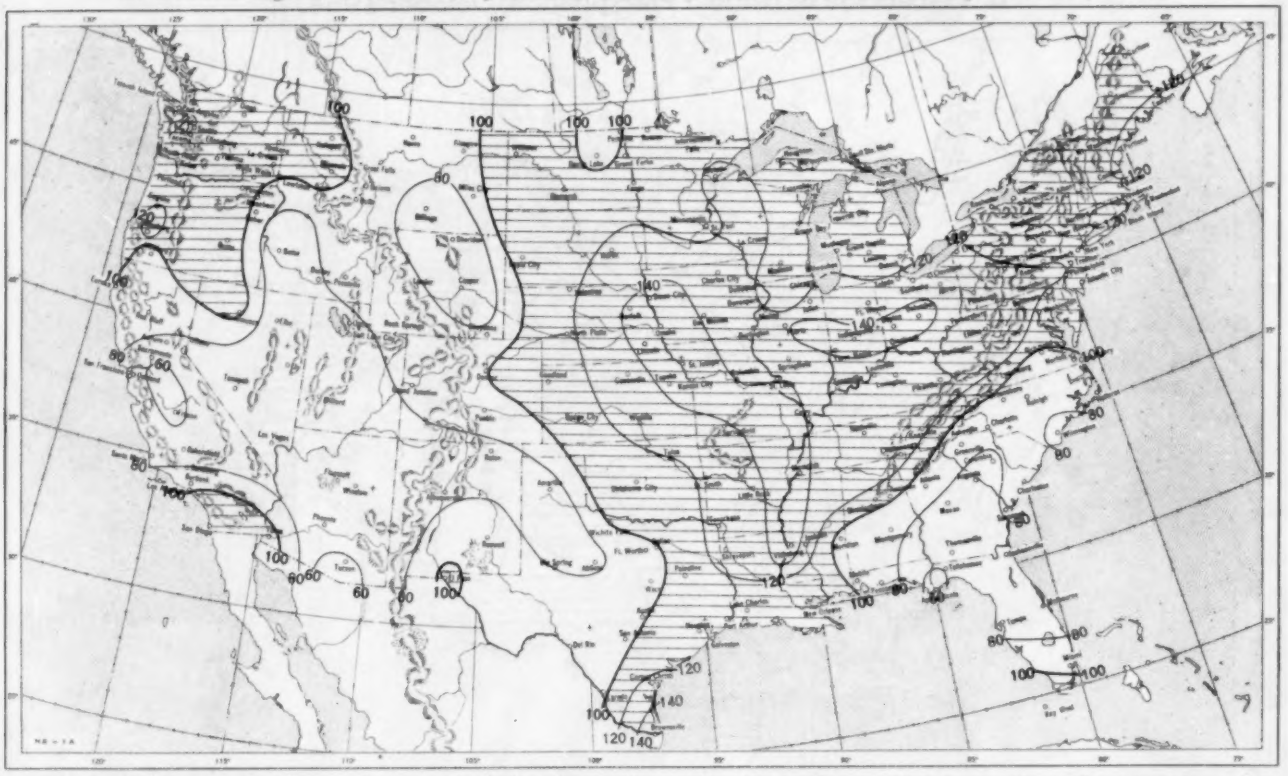


Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, October 1954.

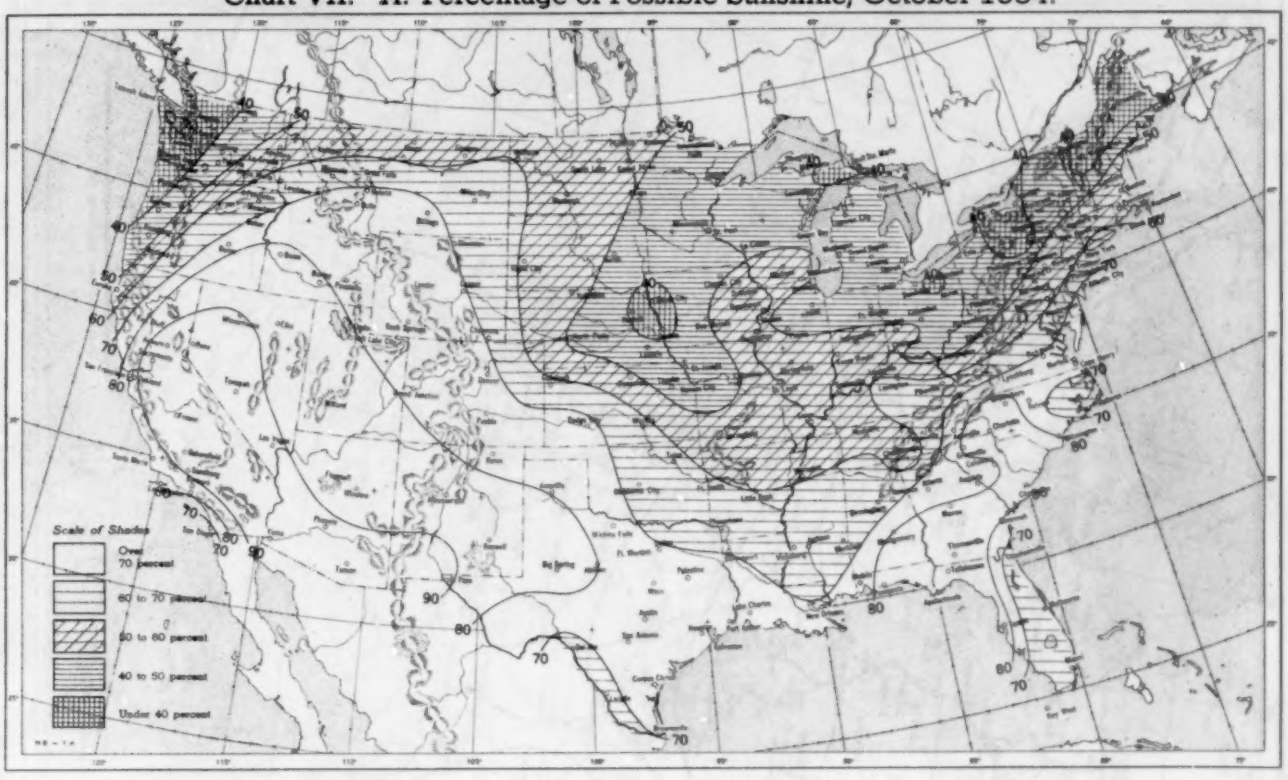



B. Percentage of Normal Sky Cover Between Sunrise and Sunset, October 1954.

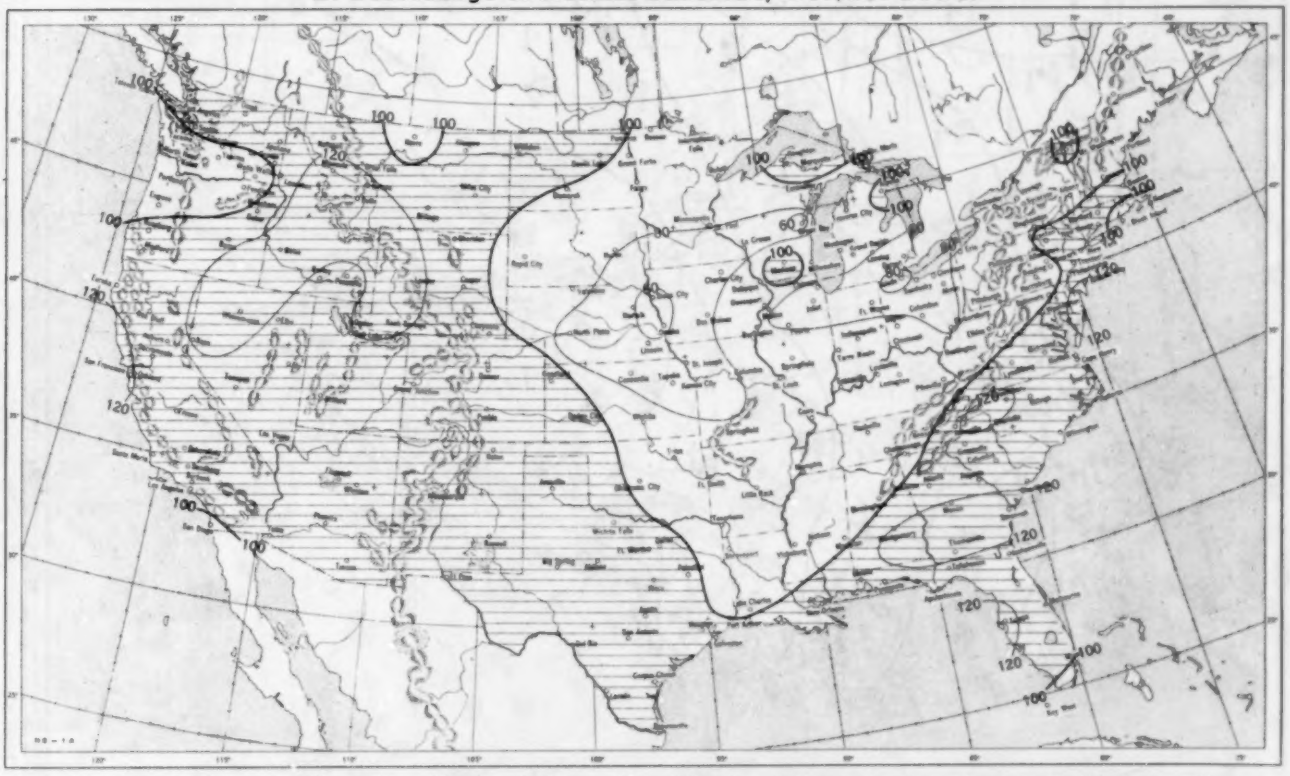


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

## Chart VII. A. Percentage of Possible Sunshine, October 1954.




## B. Percentage of Normal Sunshine, October 1954.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

## Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, October 1954. Inset: Percentage of Normal

### Average Daily Solar Radiation, October 1954.

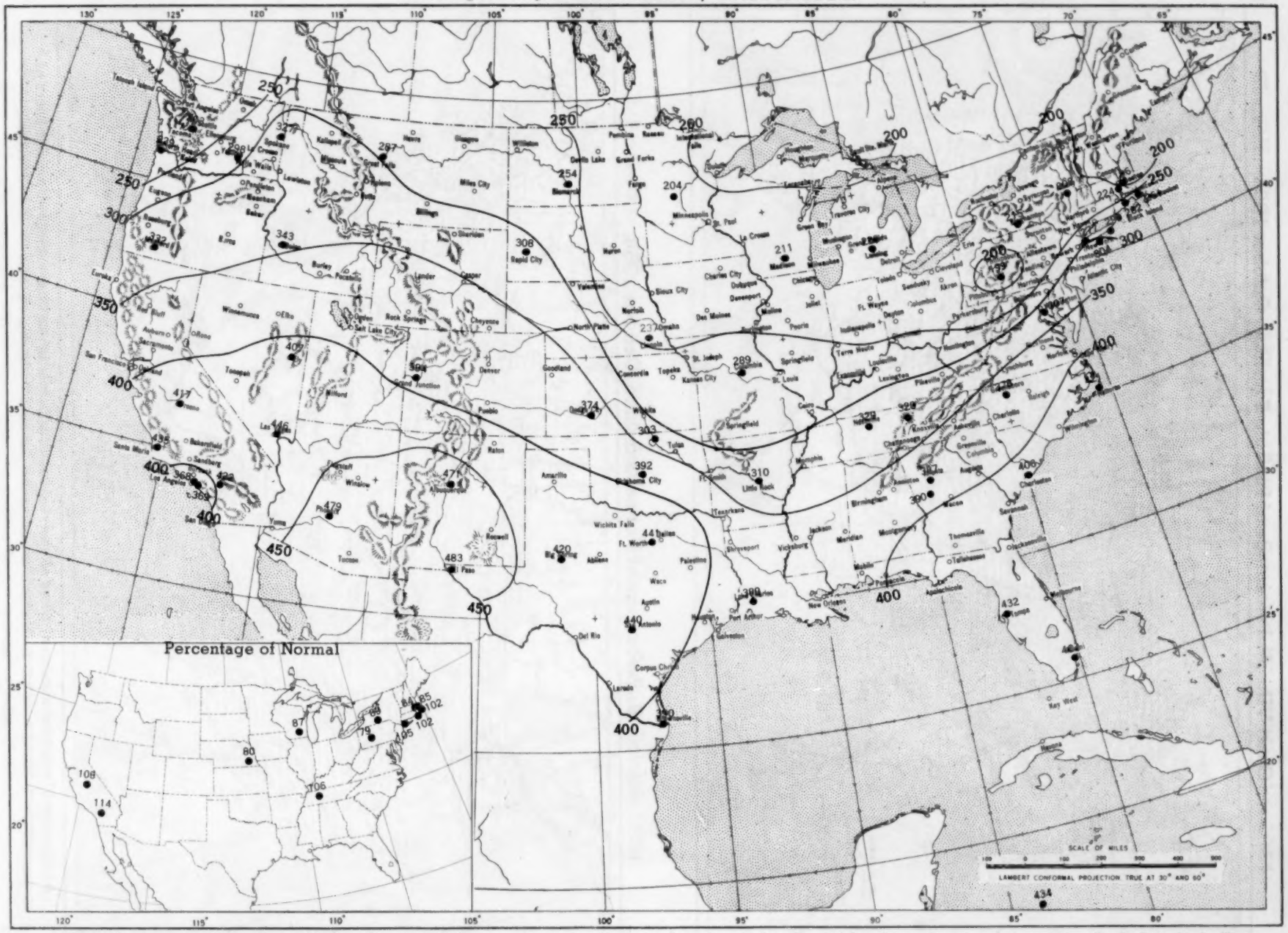
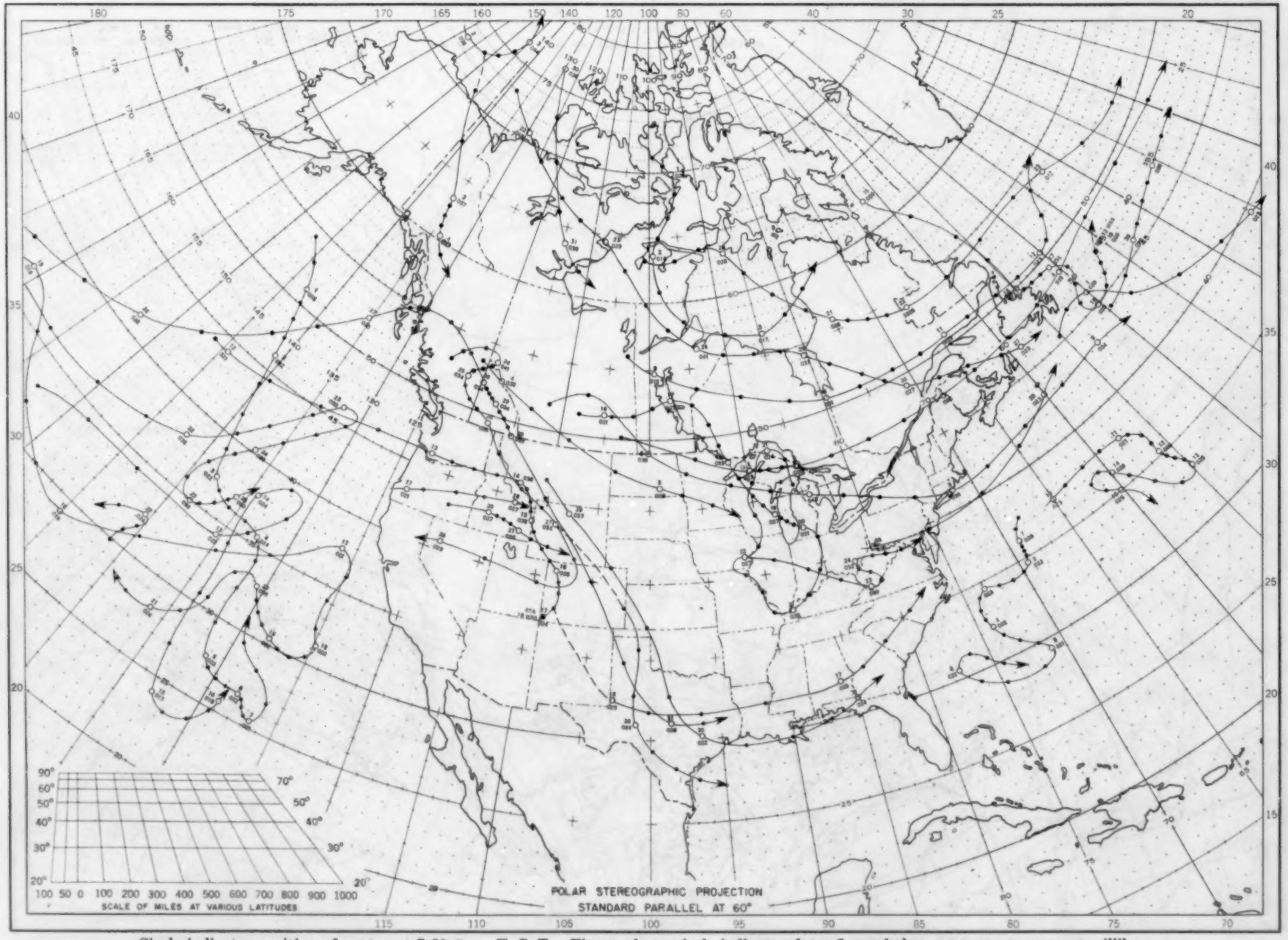


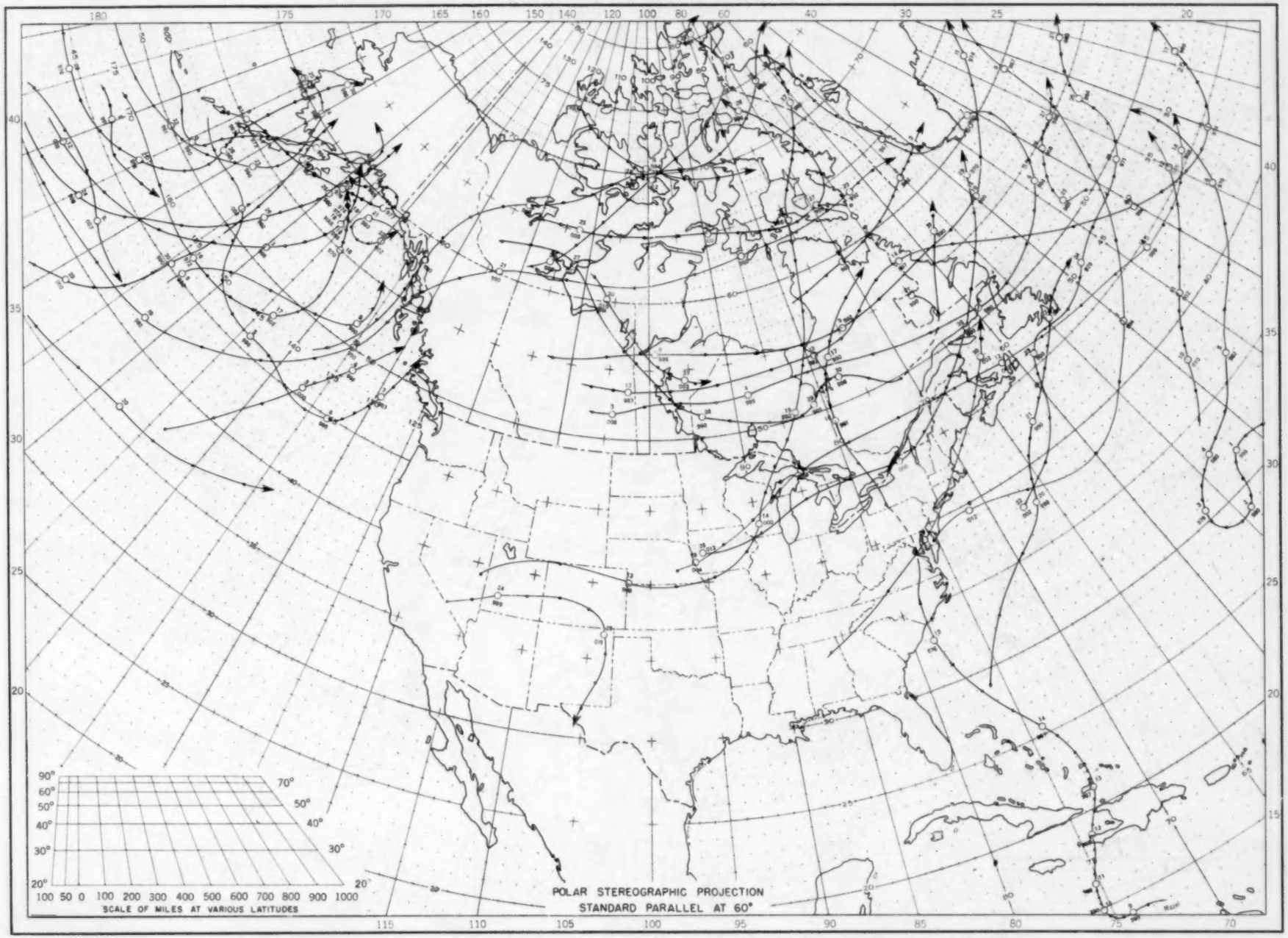

Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

## Chart IX. Tracks of Centers of Anticyclones at Sea Level, October 1954.


SCALE OF MILES AT VARIOUS LATITUDES
100 50 0 100 200 300 400 500 600 700 800 900 1000
POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°

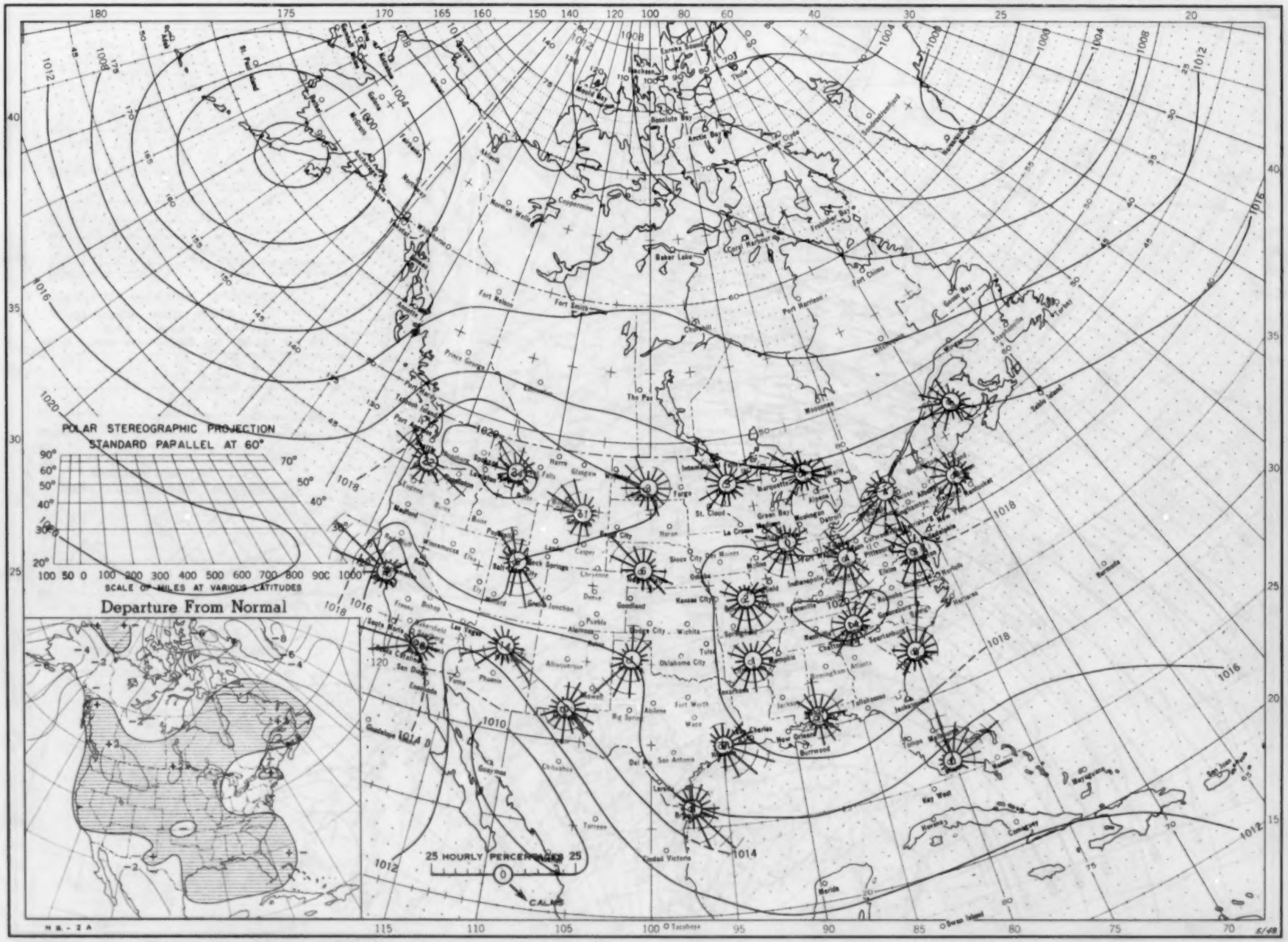
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

## Chart X. Tracks of Centers of Cyclones at Sea Level, October 1954.


POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°
SCALE OF MILES AT VARIOUS LATITUDES
100 50 0 100 200 300 400 500 600 700 800 900 1000

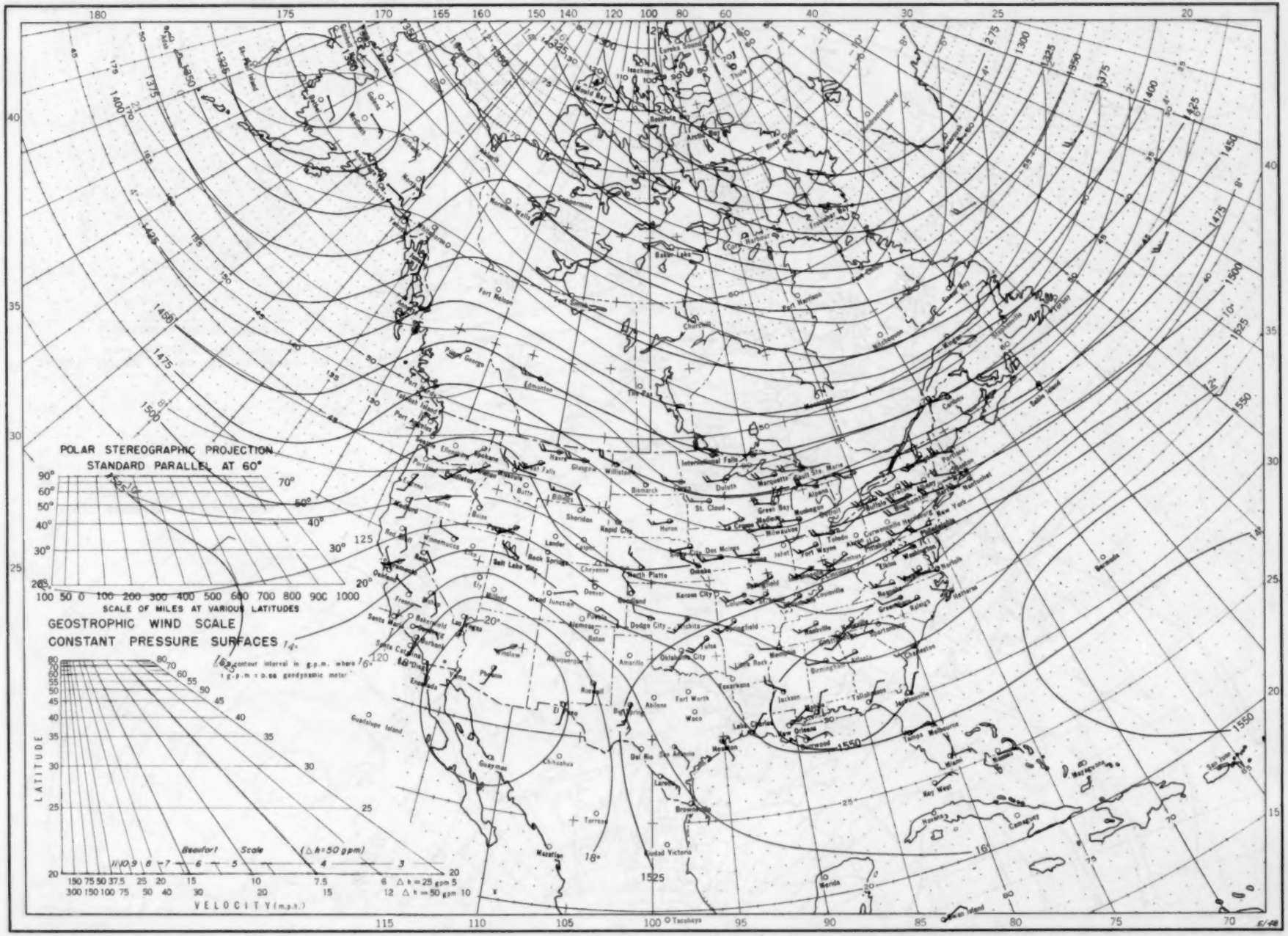
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, October 1954. Inset: Departure of Average Pressure (mb.) from Normal, October 1954.



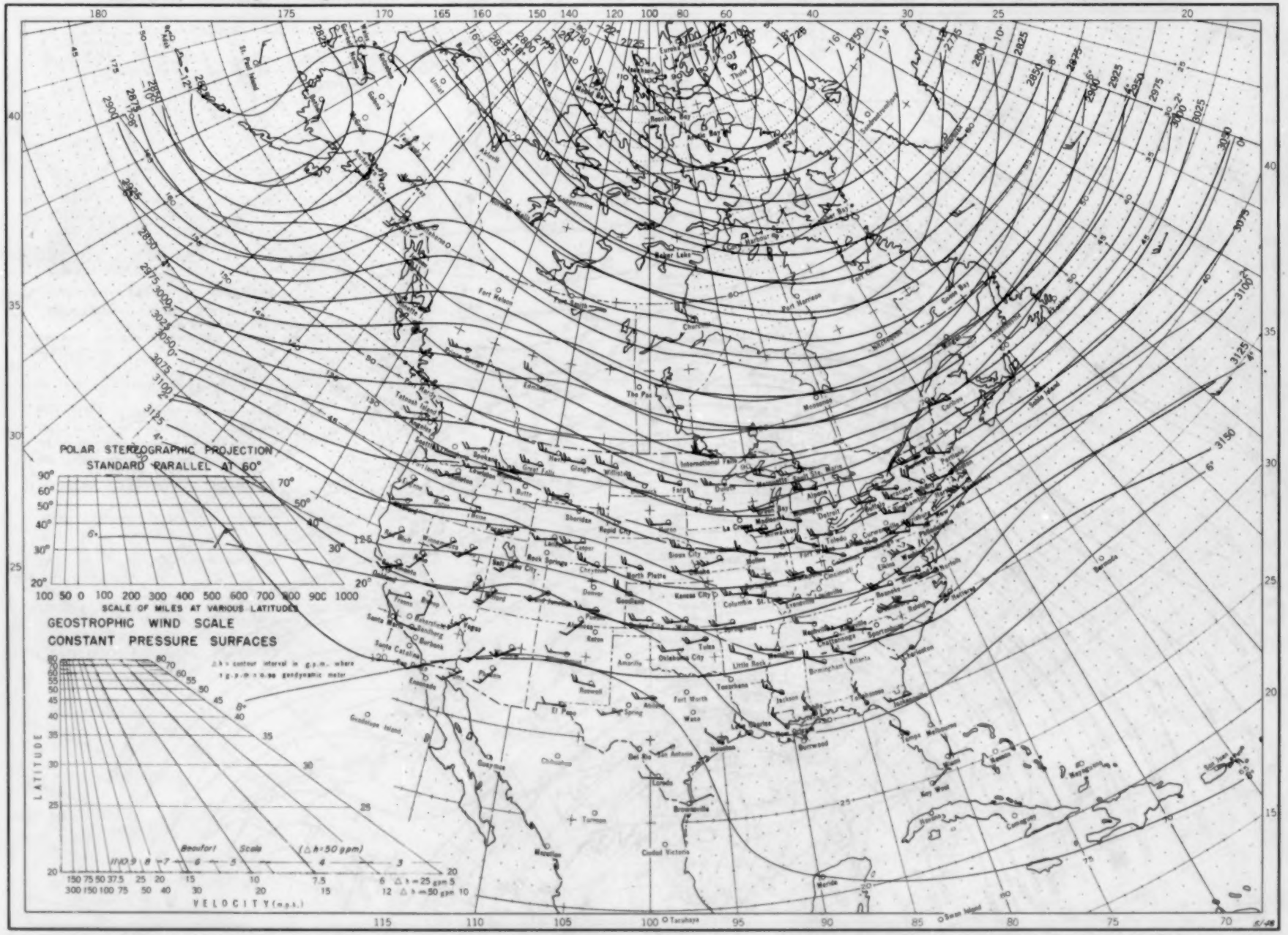

Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), October 1954.



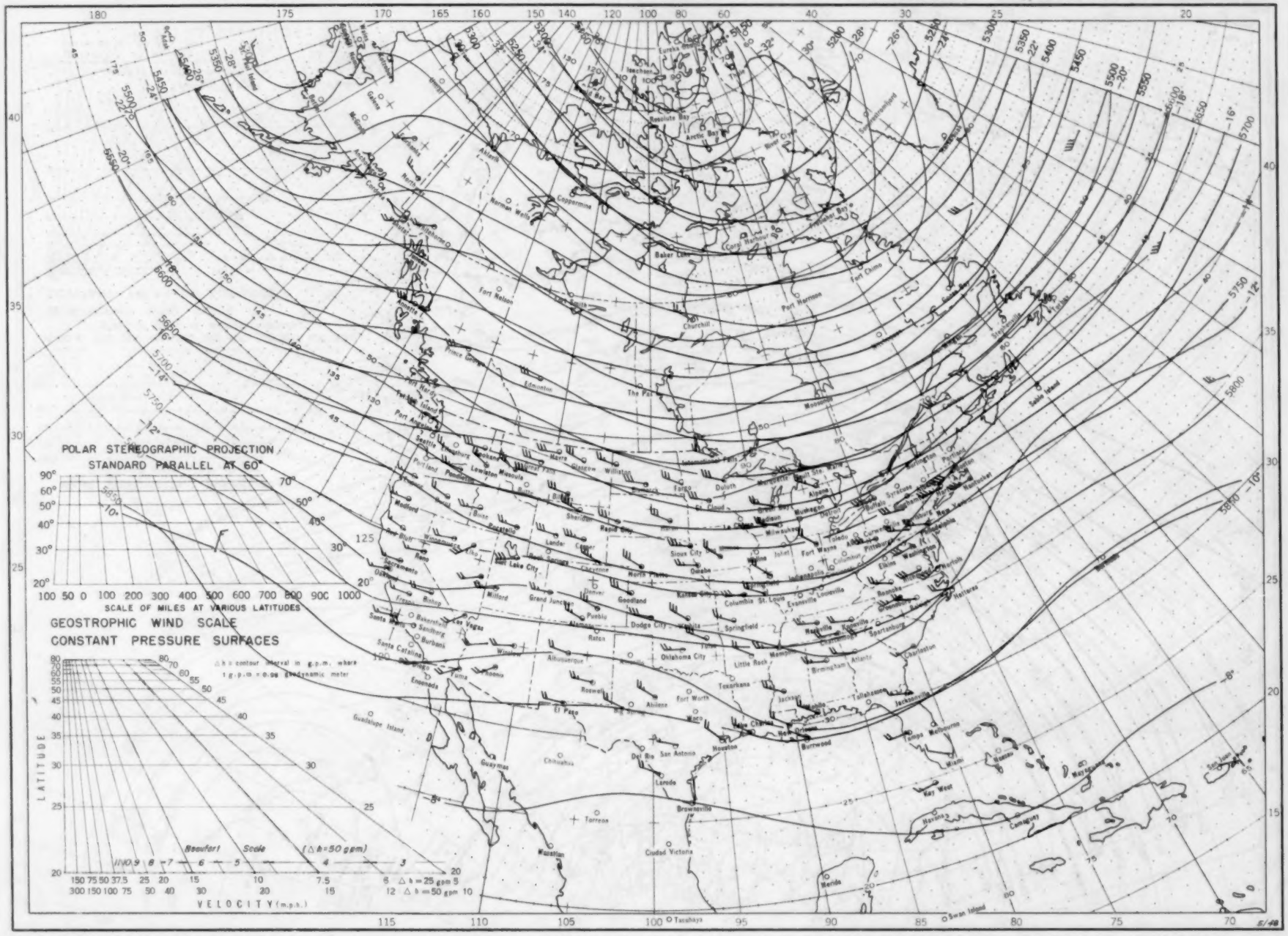

Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

## Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), October 1954.



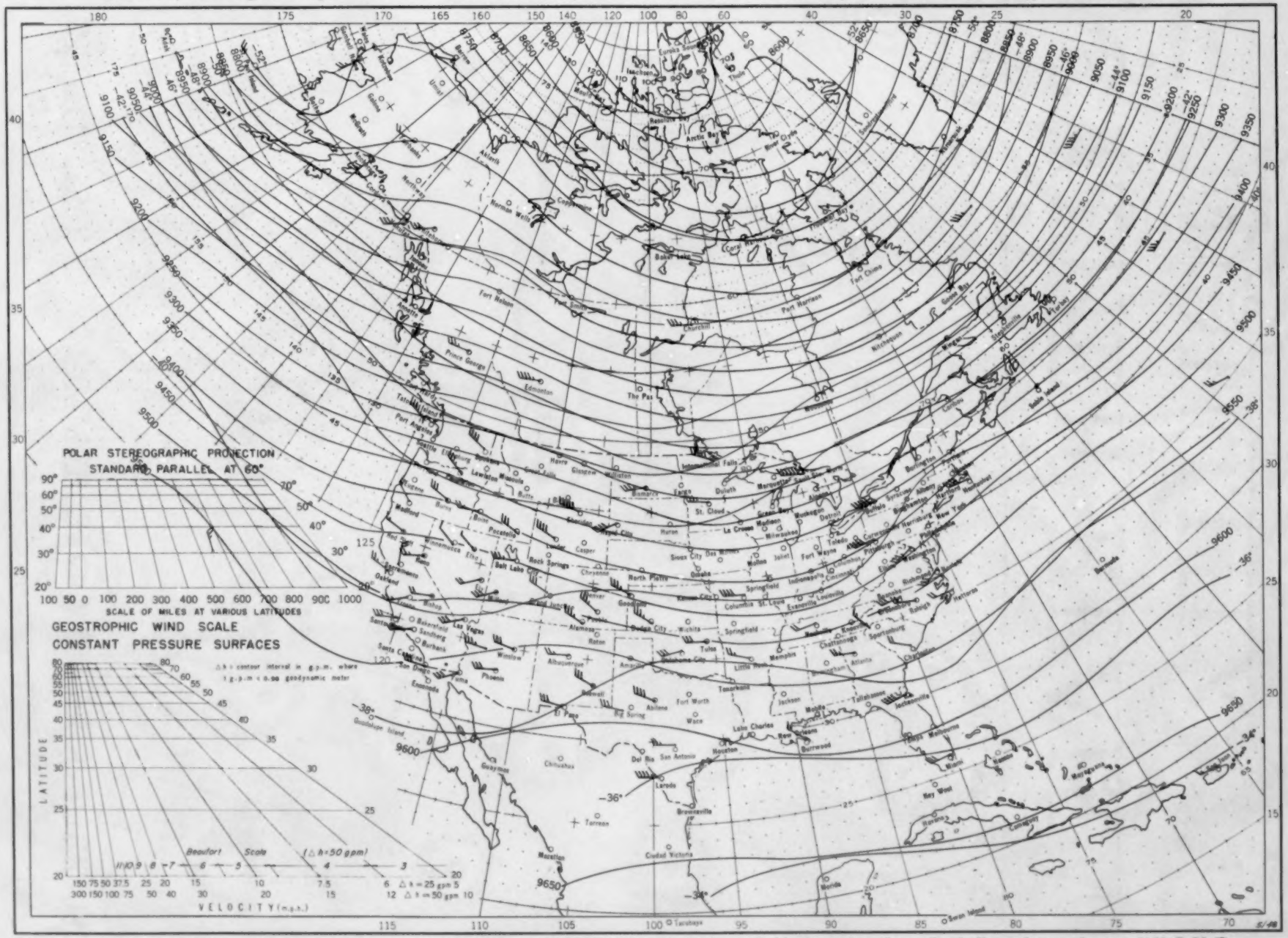

Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

## Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), October 1954.




Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), October 1954.




Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.